THE NOvA EXPERIMENT: LATEST RESULTS

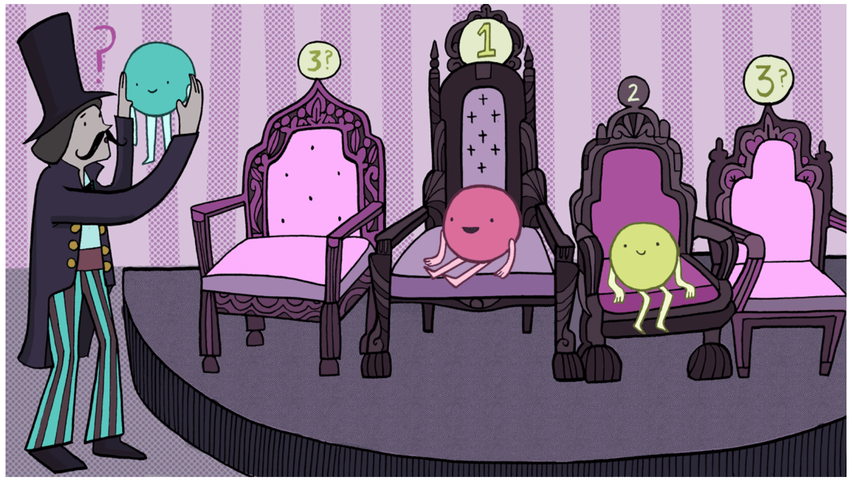
Alexander Booth, for the NOvA Collaboration

International Symposium on Neutrino Physics & Beyond, Hong Kong

February 19, 2024

Queen Mary
University of London

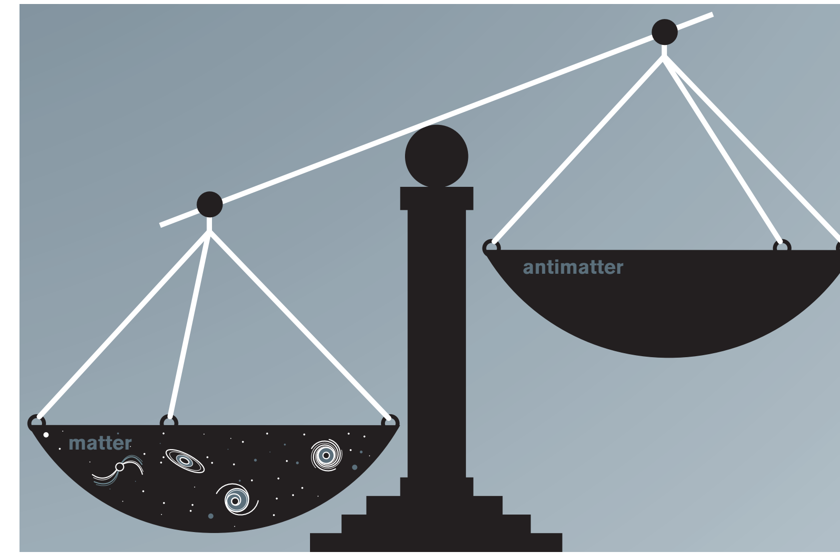
Open Questions



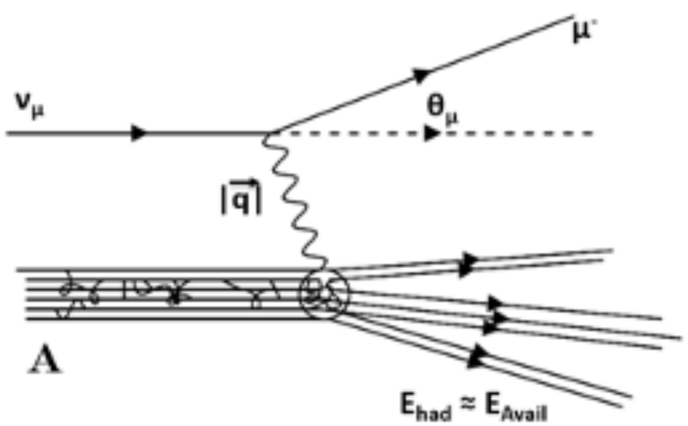
Sandbox Studio, Chicago

What is the neutrino mass ordering?

Do neutrinos violate CP symmetry?



Sandbox Studio, Chicago

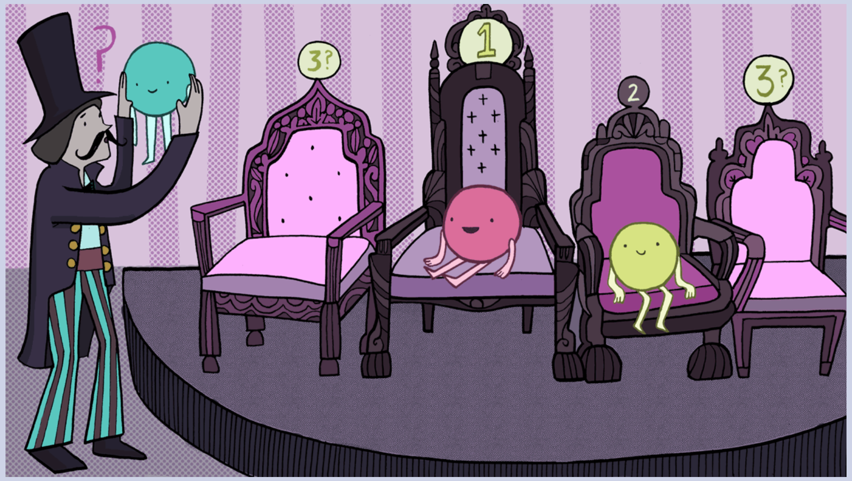


How are nuclear effects changing the interaction probability of neutrinos?

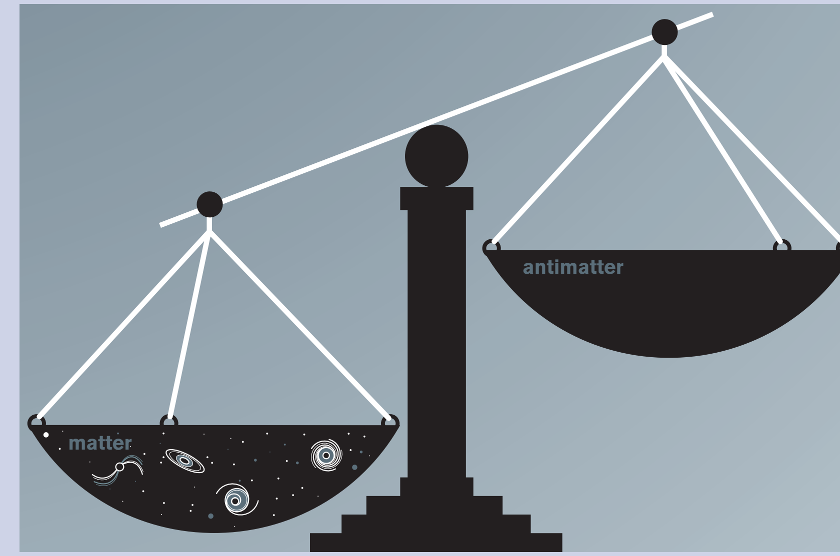
Are 3-flavour oscillations the full picture?

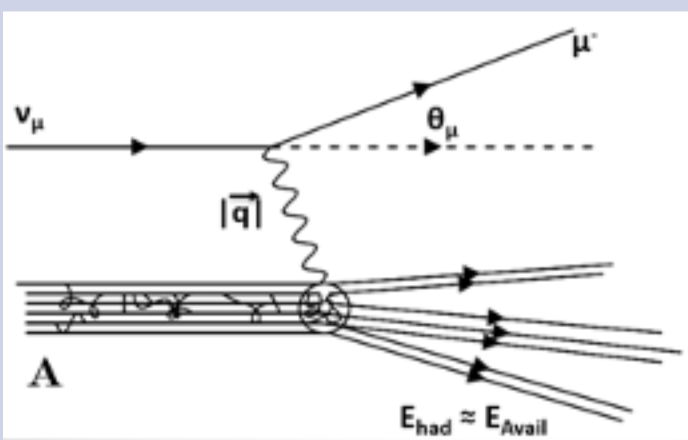
Sandbox Studio, Chicago

In This Talk…



3 flavour oscillations via a new, alternative statistical treatment.

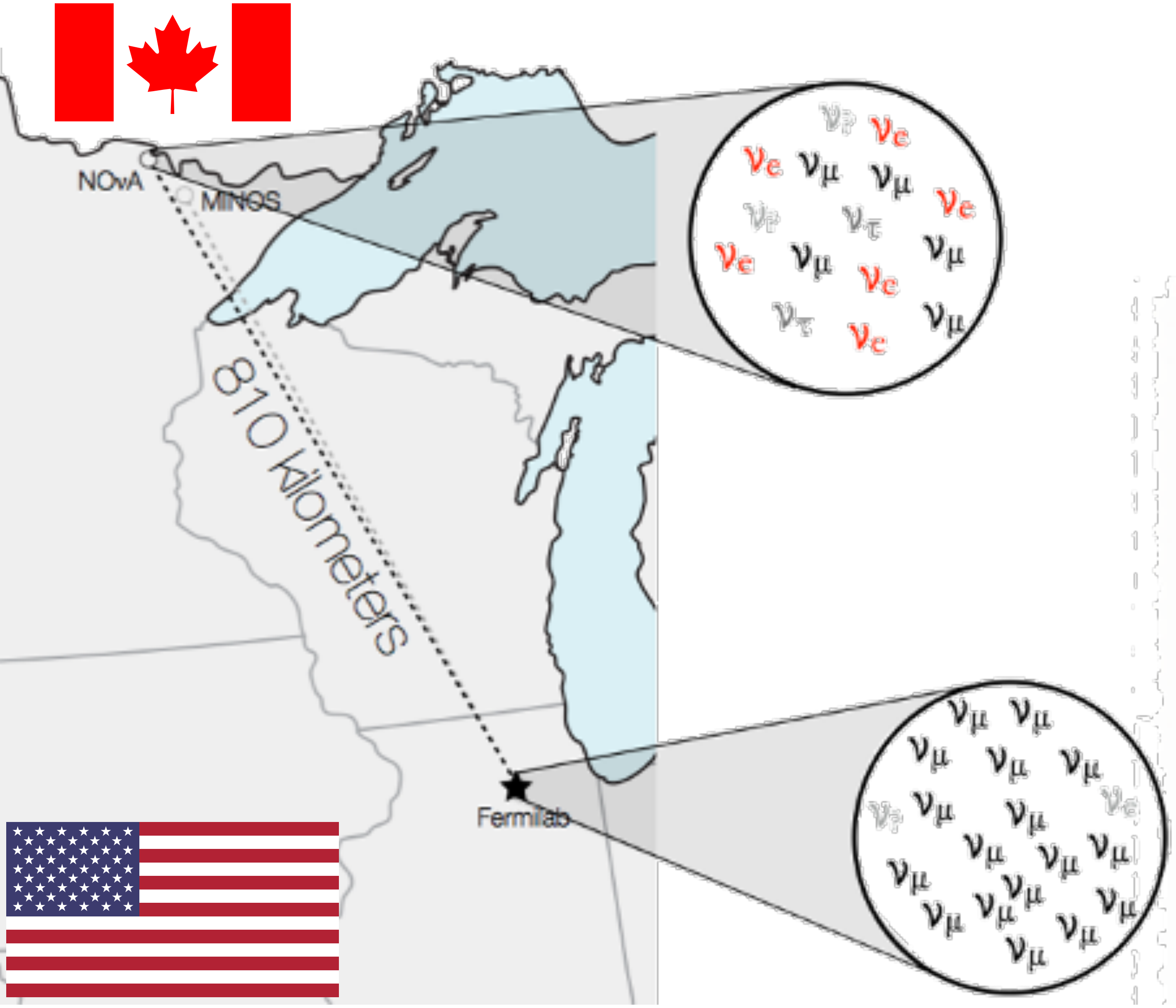


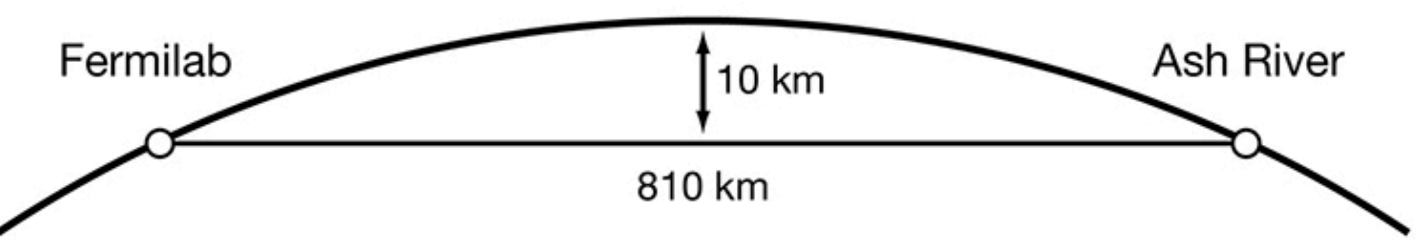


New ν_μ CC cross section measurement with a focus on nuclear effects - e.g. 2p2h/MEC interactions.

Phys.Rev.Lett. 127 (2021) 20, 201801 →

NOvA Overview



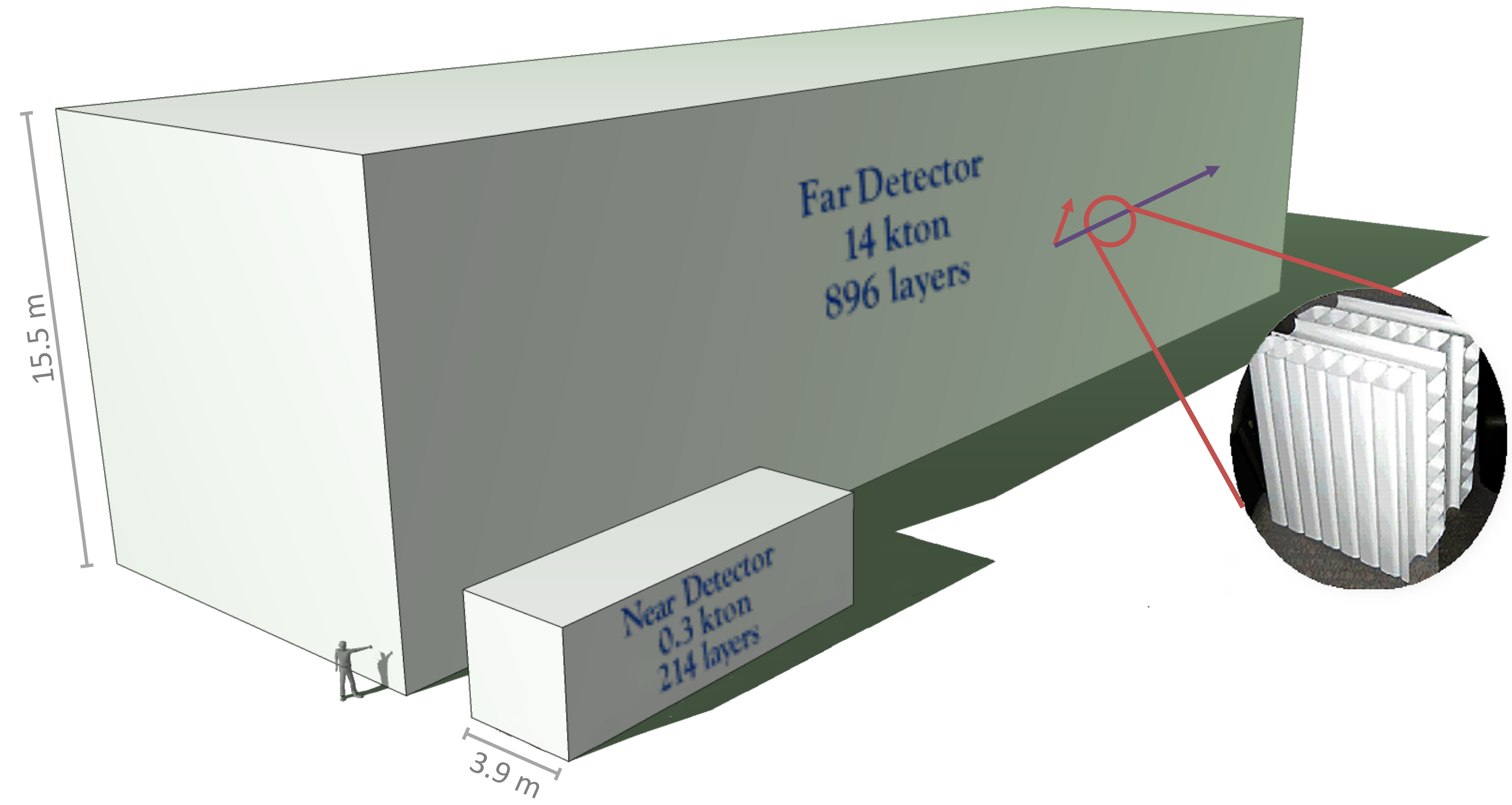


- Long-baseline neutrino oscillation experiment.
  - NuMI **neutrino beam** at Fermilab.
  - **Near detector** to measure beam before oscillations.
  - **Far detector** measures the oscillated spectrum.

- **Primary goals are to** study 3-flavour oscillations via:
  - $\nu_\mu \rightarrow \nu_\mu$, $\nu_\mu \rightarrow \nu_e$
  - $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$, $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

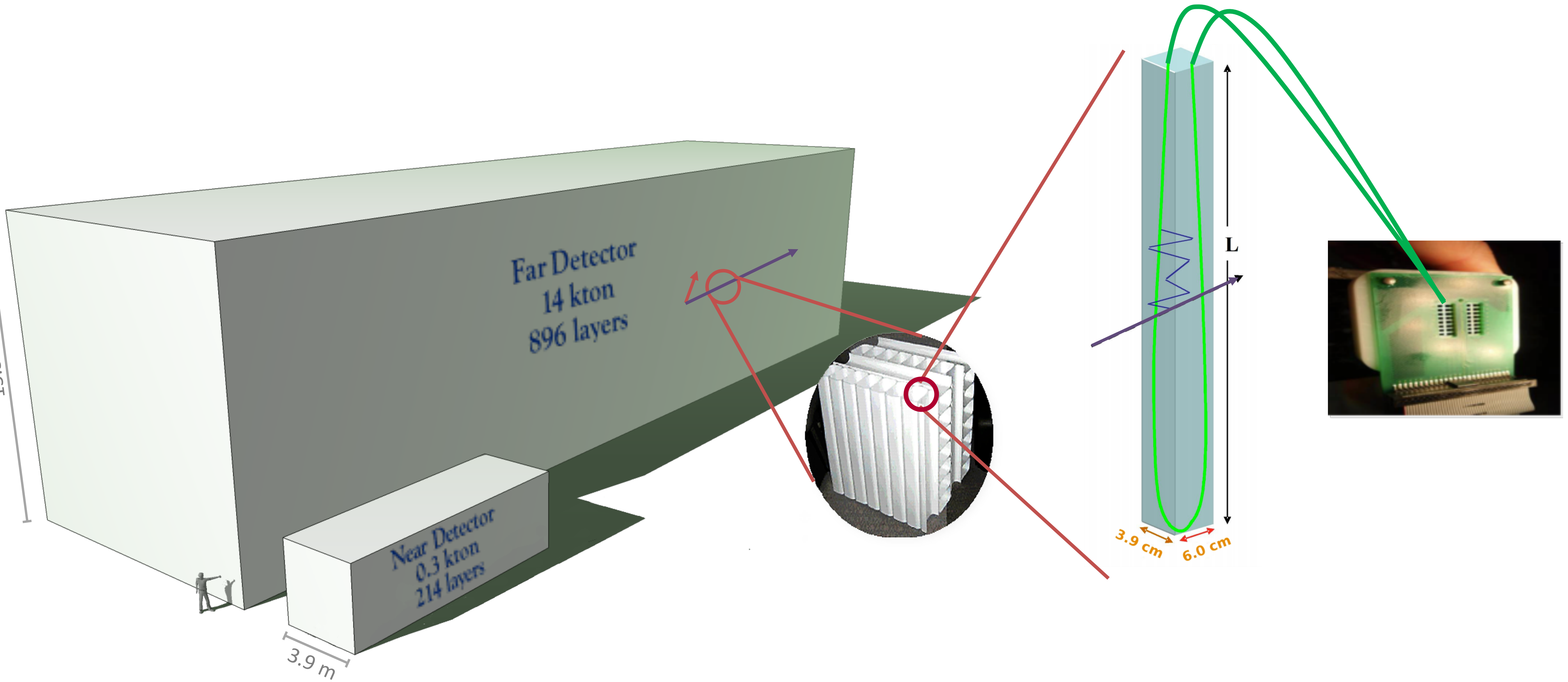
  and measure neutrino cross sections.

The NOvA Detectors



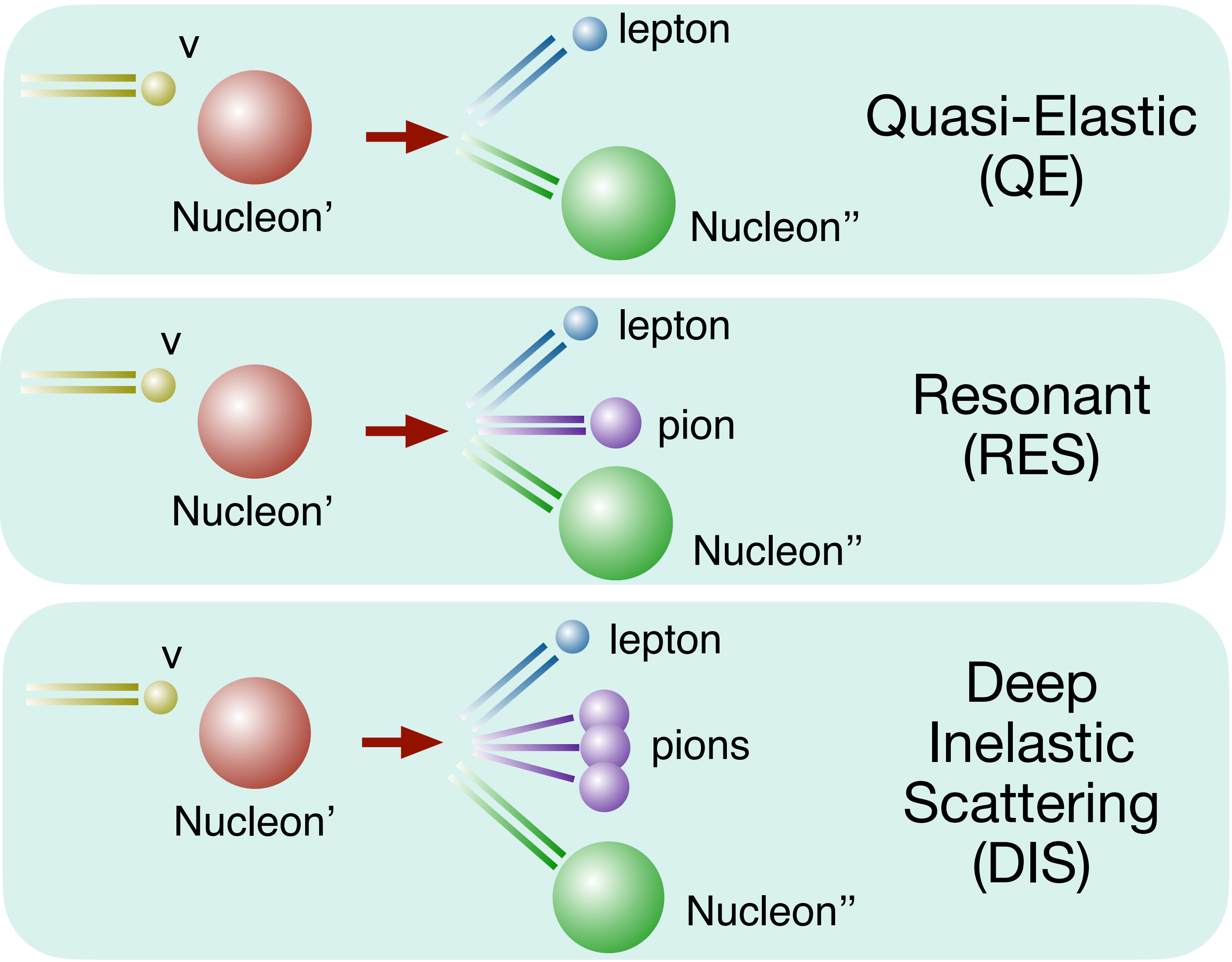
- Both are large, (FD 60 m long).
- Functionally identical: consist of extruded PVC cells filled with 11 million litres of liquid scintillator.
- Arranged in alternating directions for 3D reconstruction.

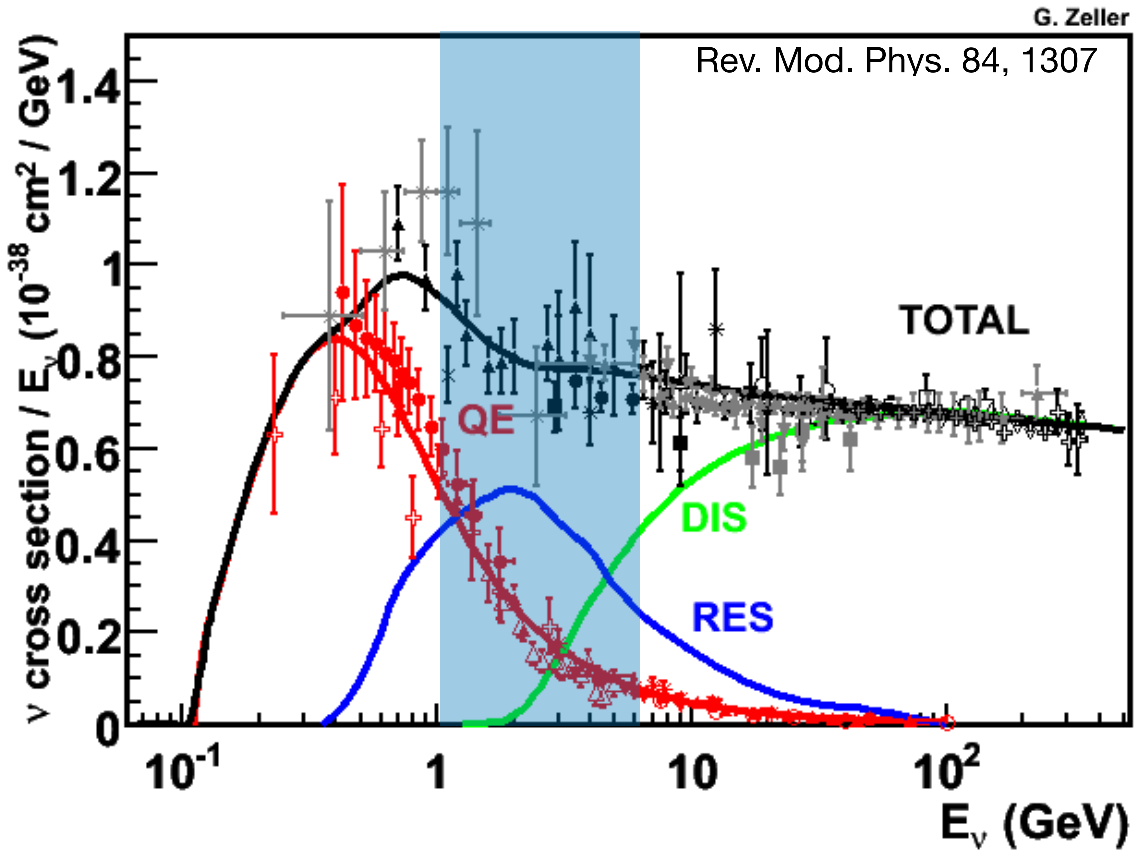
The NOvA Detectors



- Light produced when charged particle passes through cells.
- The light is picked up by wavelength shifting fibre. Transported to an Avalanche PhotoDiode - light collected and amplified.
- Image hadronic recoil system to ~ 5 MeV / cell sensitivity and ~ cm-scale tracking resolution.

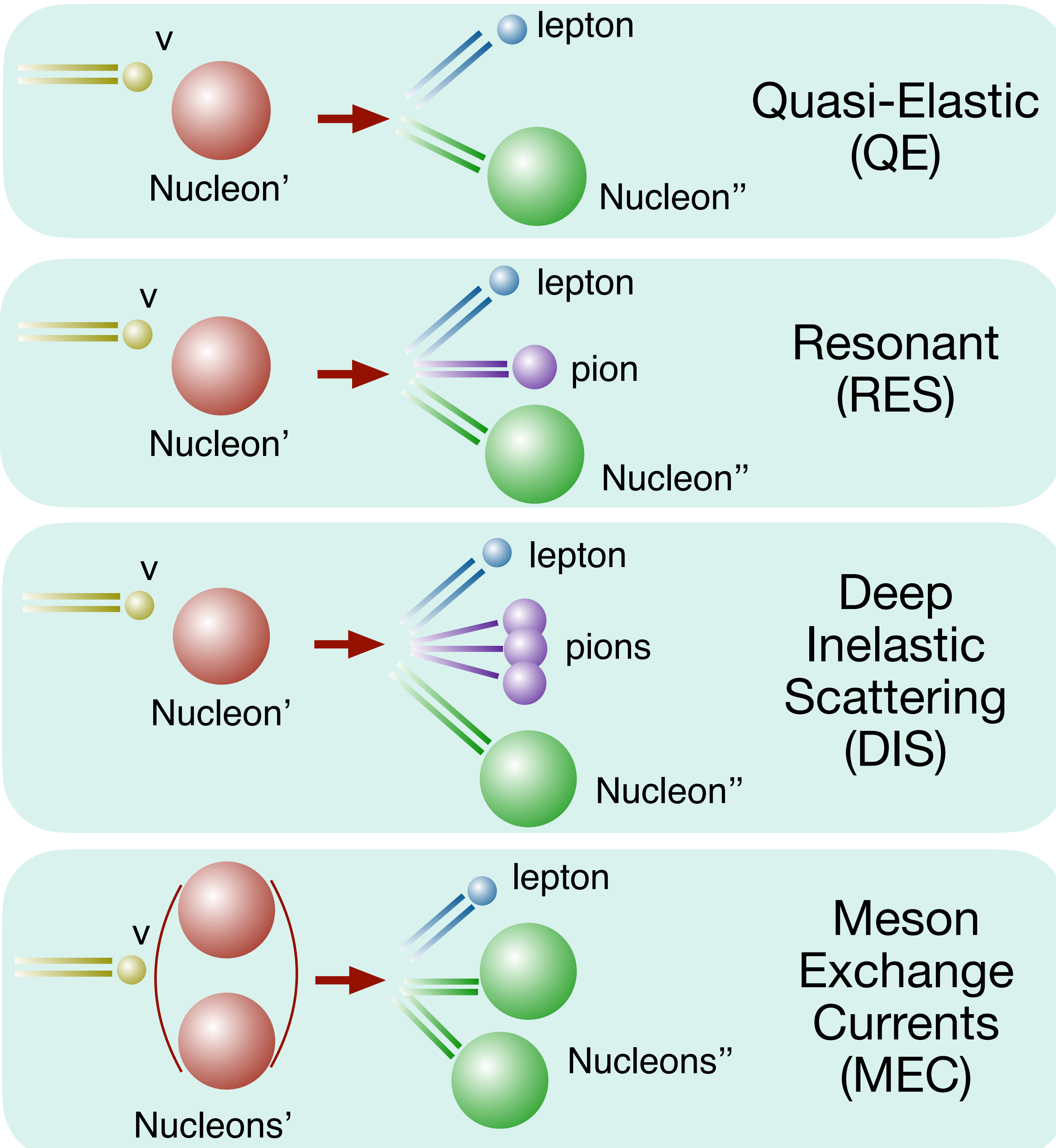
Neutrino Interaction Types

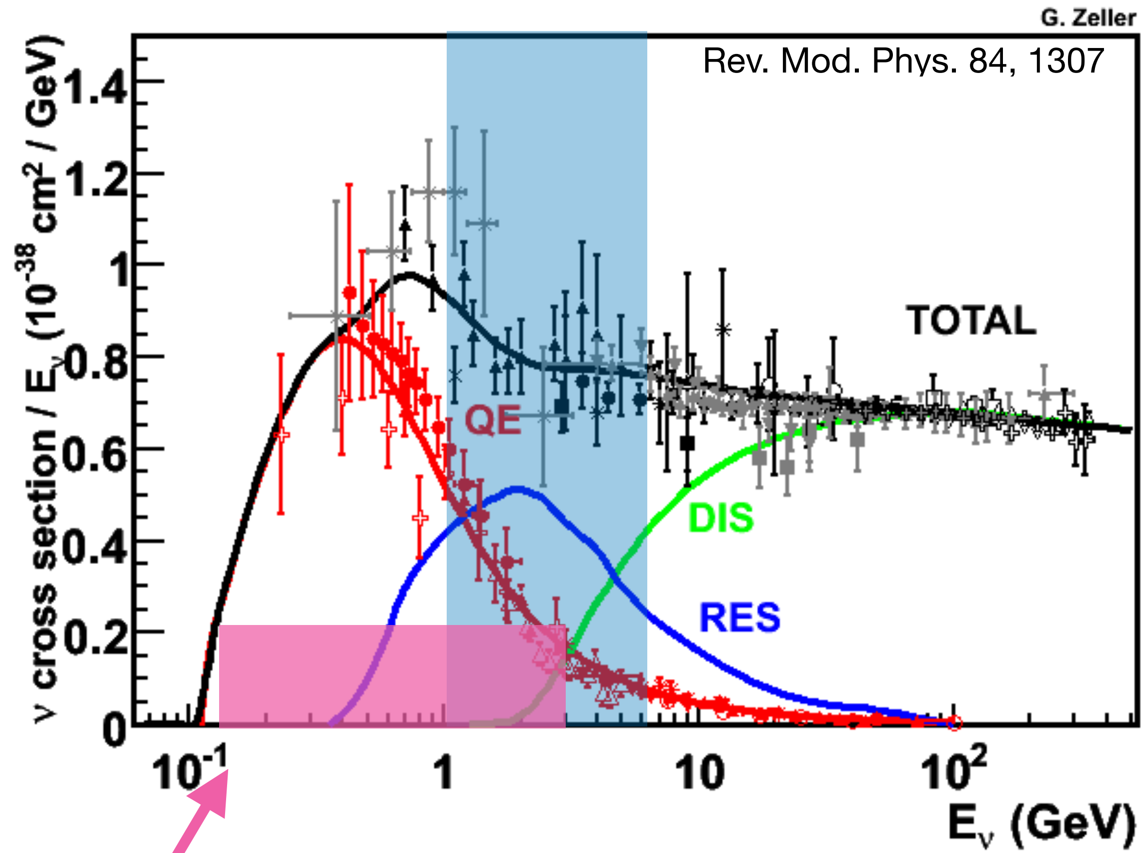




- All interaction types can be studied with huge statistics.

Neutrino Interaction Types





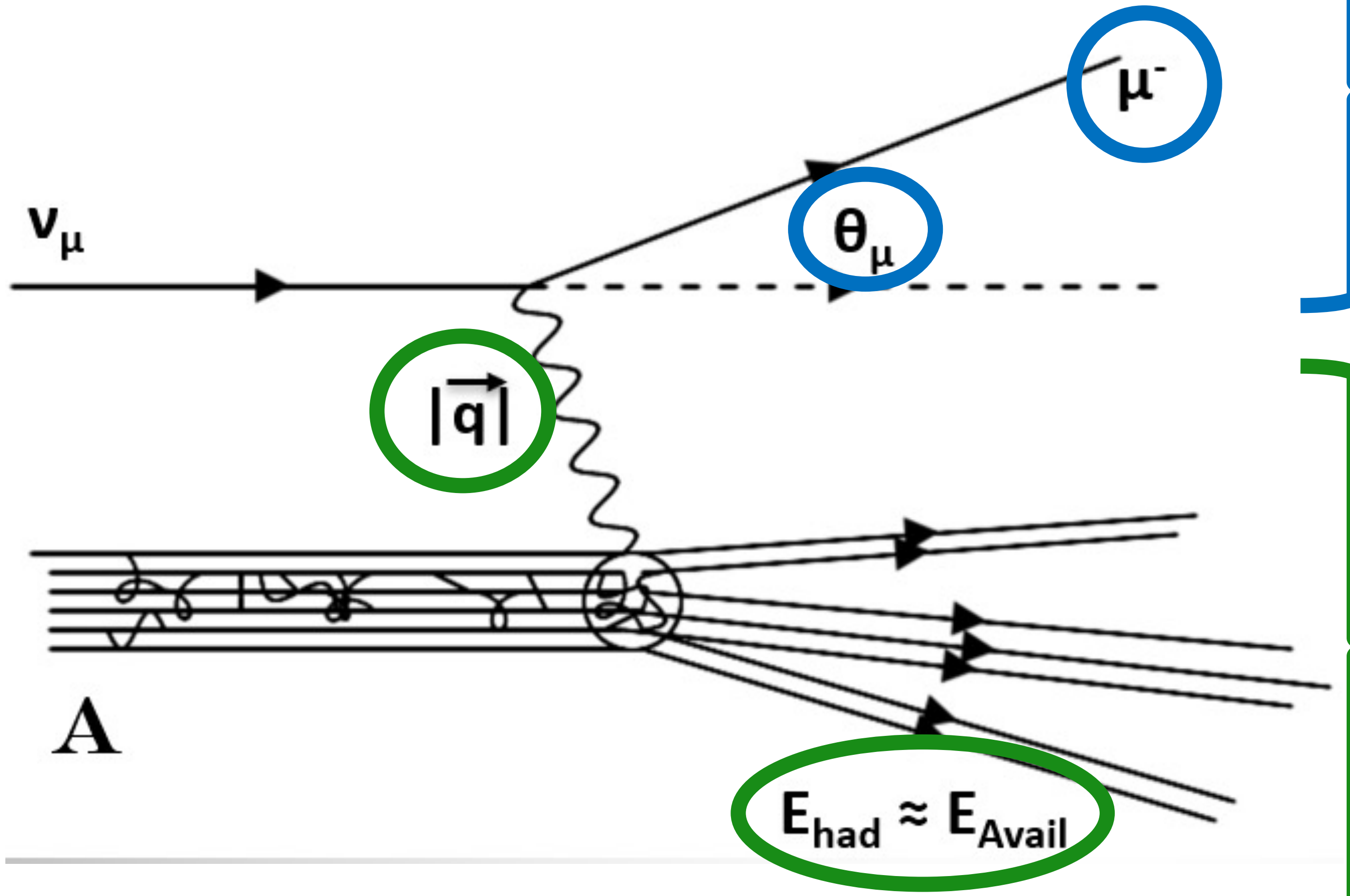
- All interaction types can be studied with huge statistics.
- Nuclear effects are significant.
- A better understanding is important for reducing systematics on oscillation measurements.

Cross Section Result

ν_μ CC Cross Section Result(s)

(Both) double differential.

(Both) focus on sensitivity to 2p2h / MEC events.

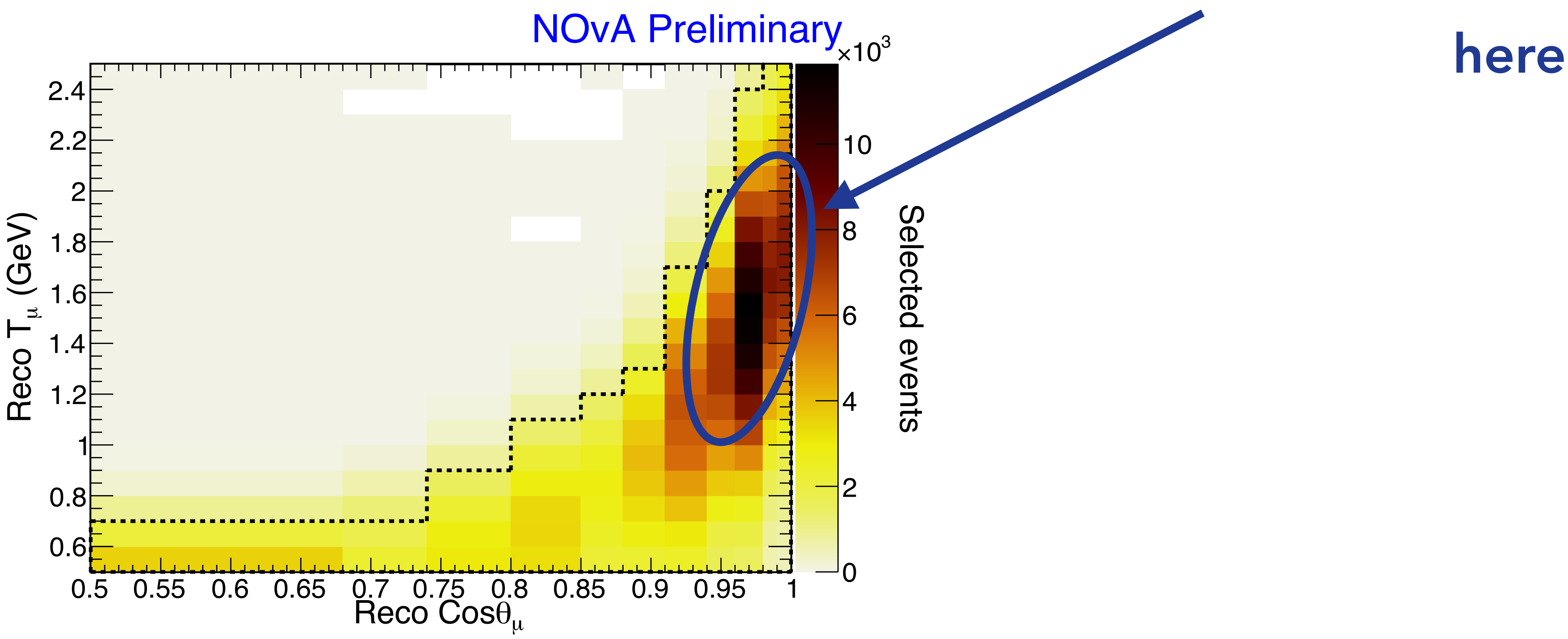


Muon System ⇨ Energy **vs** angle

Hadronic System ⇨ 3-momentum transfer $|\vec{q}|$ **vs** energy

Muon System

- **Exclusive**: events must have exactly one reconstructed track:
  - Low hadronic energy.
  - Boost MEC, reduces DIS and RES.
- Cross section reported at 115 kinematic points:
  - Typically 12 - 15% uncertainty.
  - Dominated by flux systematic.



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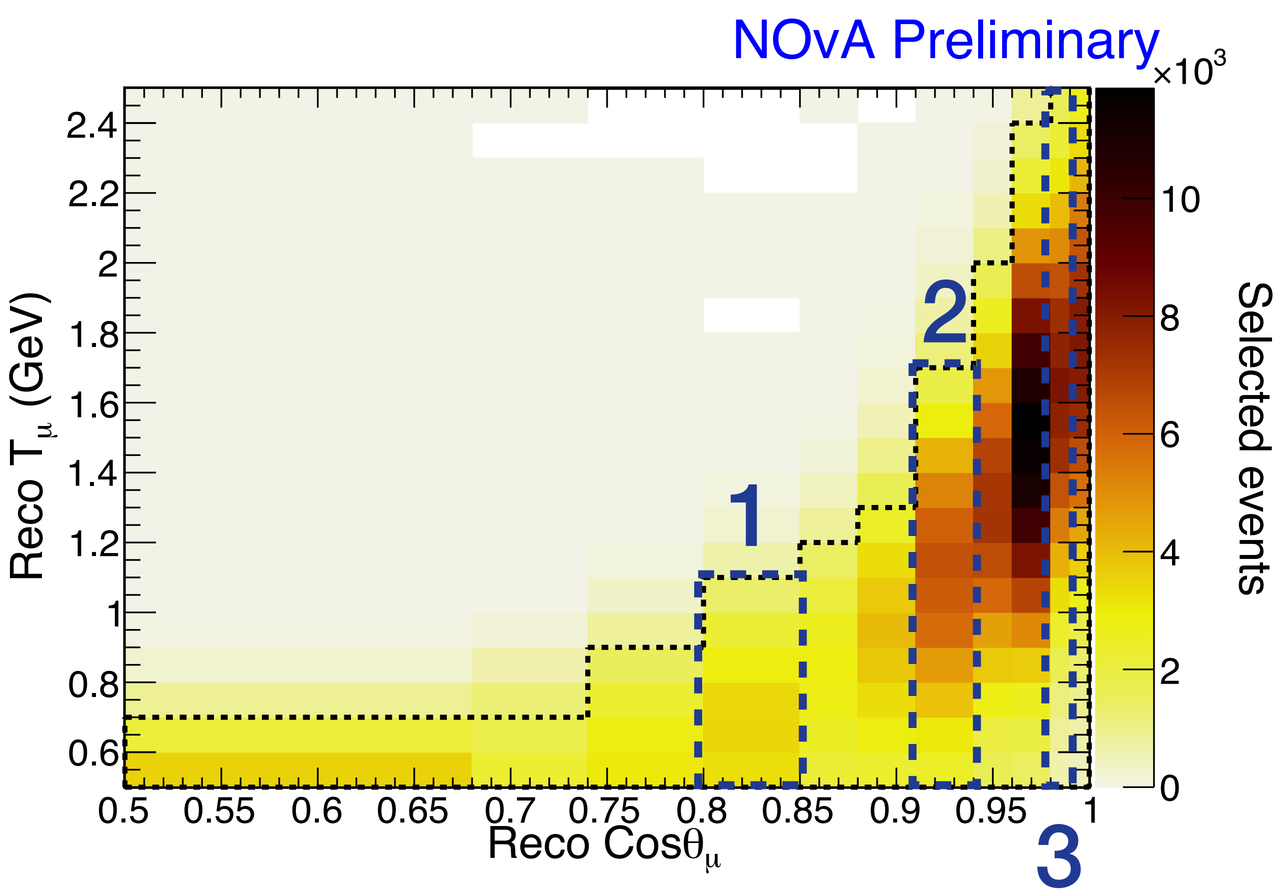
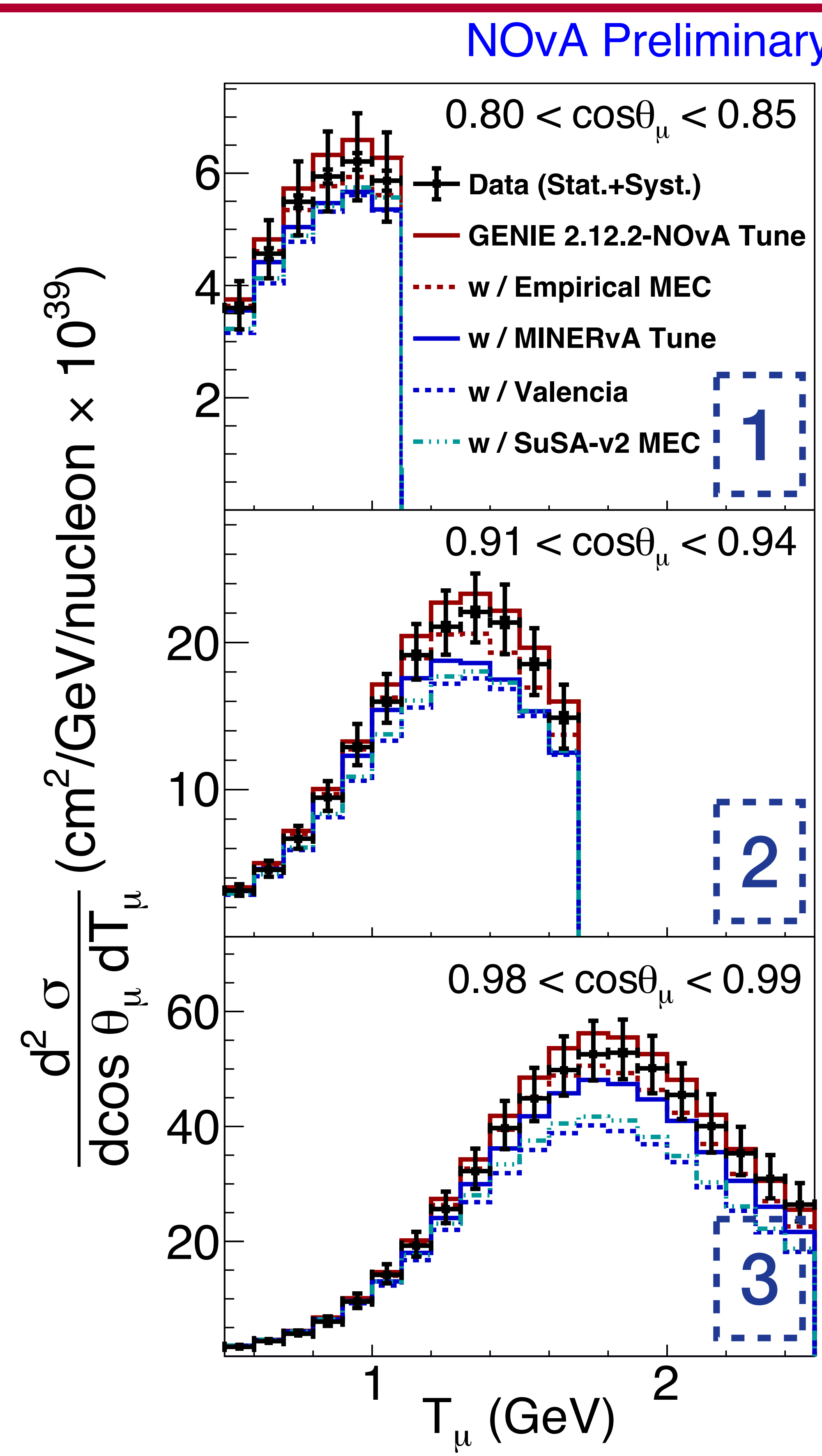




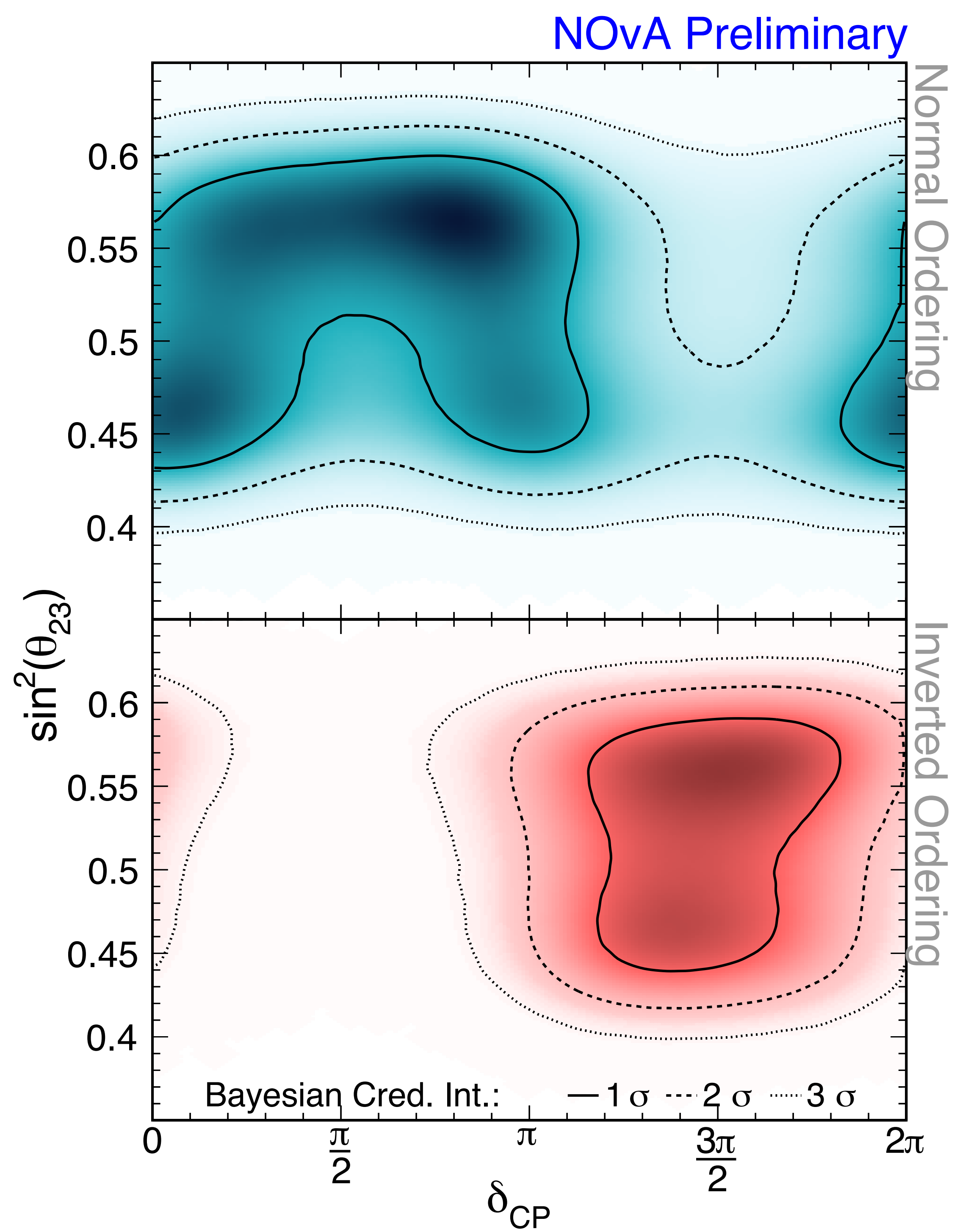
3 Flavour Oscillation Results

Alternative Statistical Treatment

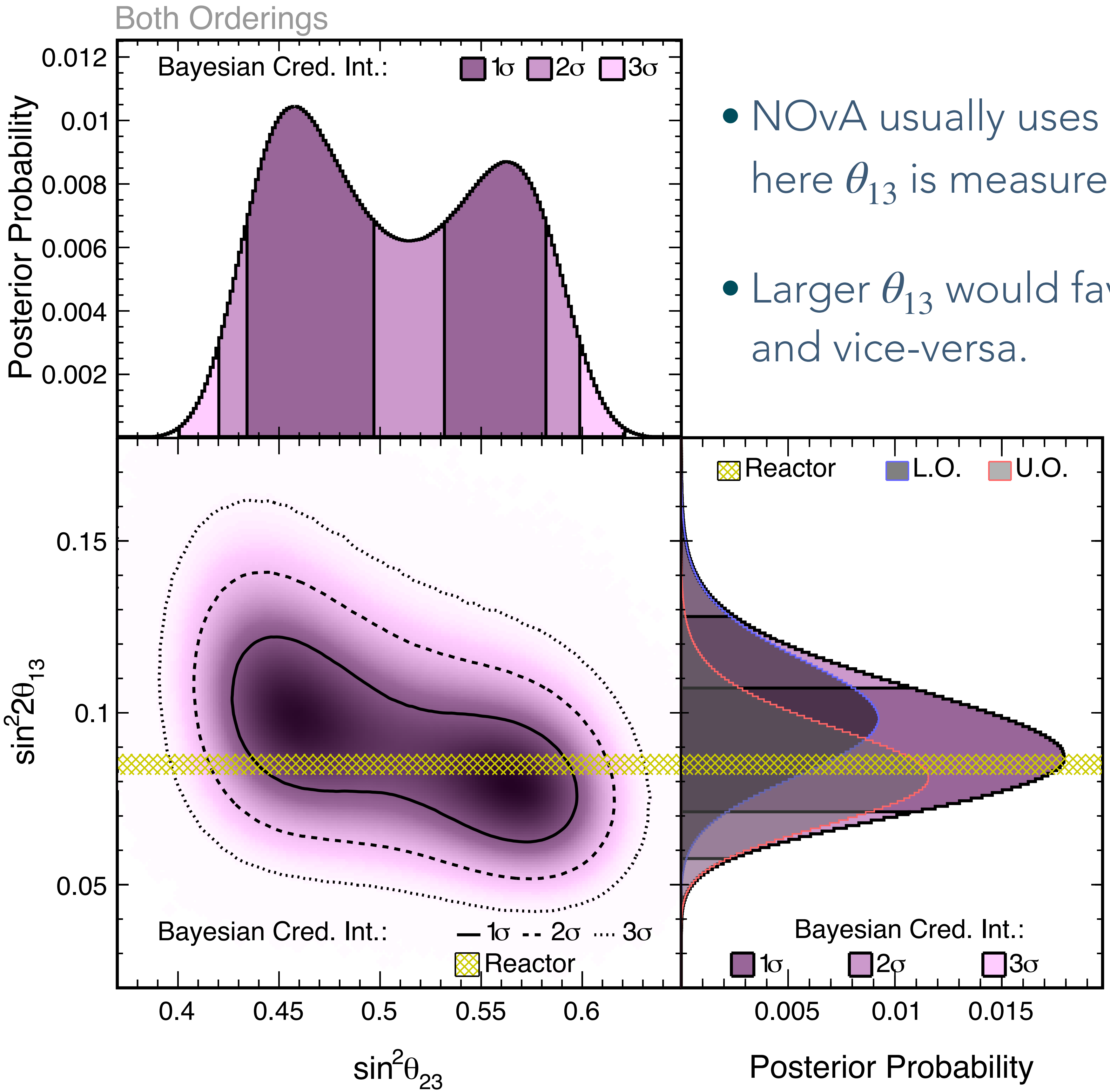
- Markov Chain Monte Carlo Bayesian analysis.
- Allows the data to be examined in new ways.
- Conclusions are the same as frequentist results, preference for the Normal Ordering and Upper Octant of $\sin^2\theta_{23}$.

Exclude IO $\delta_{CP} = \frac{\pi}{2}$ at $> 3\sigma$

Disfavour NO $\delta_{CP} = \frac{3\pi}{2}$ at ~2σ



NOvA-only θ_{13} & θ_{23}



- NOvA usually uses reactor θ_{13} constraint in the fit, here θ_{13} is measured by NOvA.
- Larger θ_{13} would favour the lower octant for θ_{23} and vice-versa.
- $\sin^2 2\theta_{13} = 0.085^{+0.020}_{-0.016}$
- Consistent with reactor experiments.

T2K-NOvA Joint Fit

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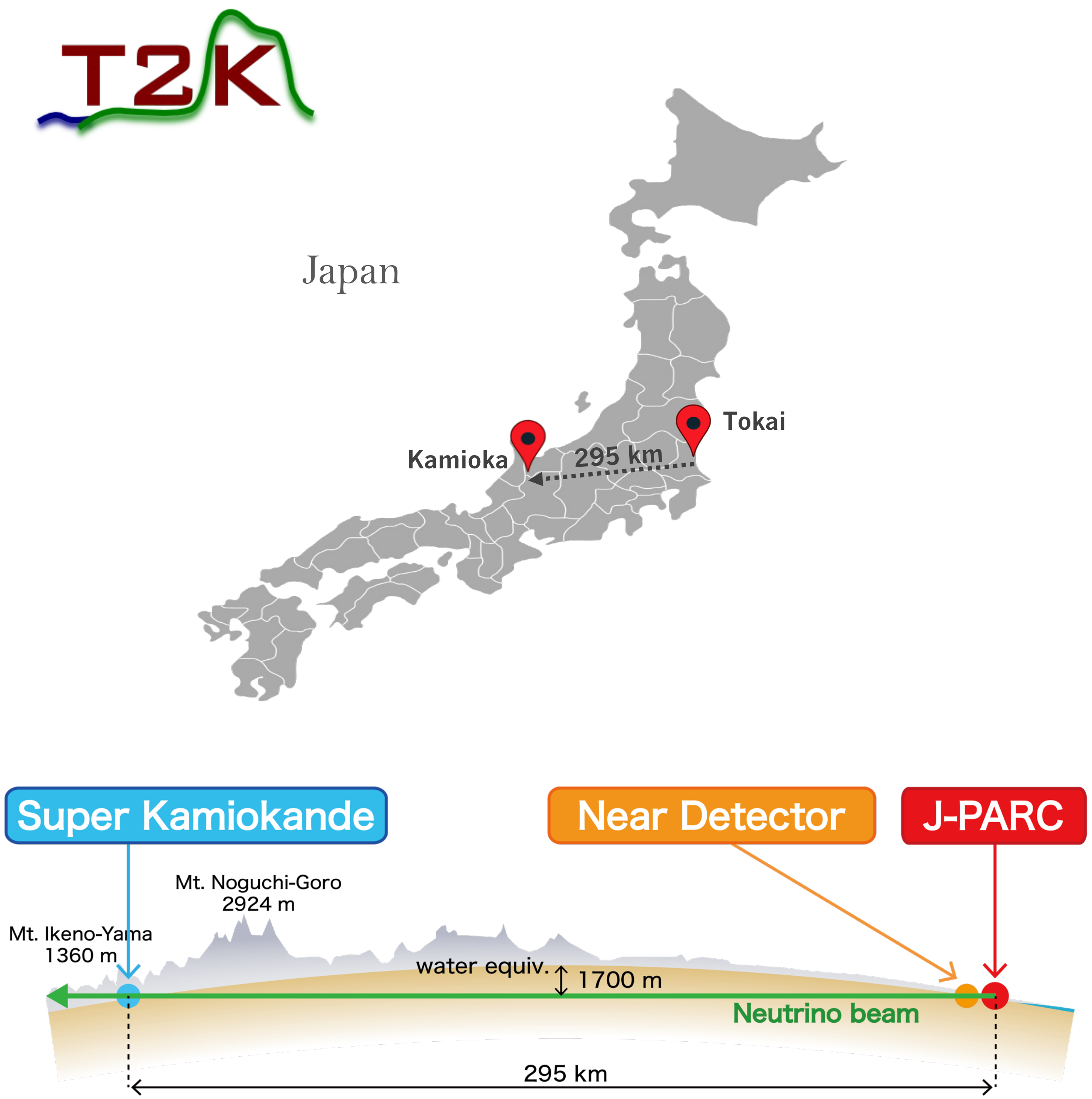
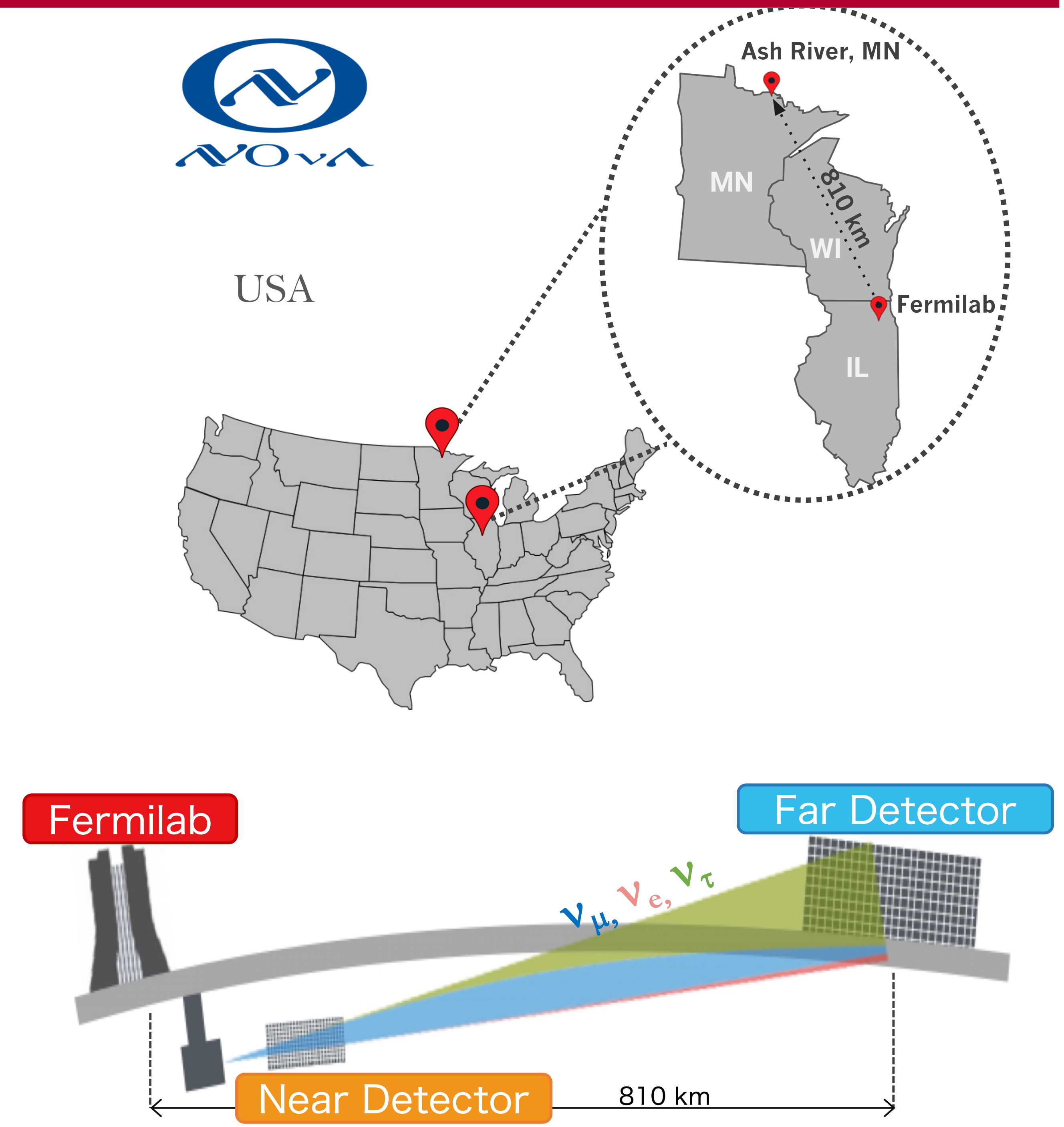
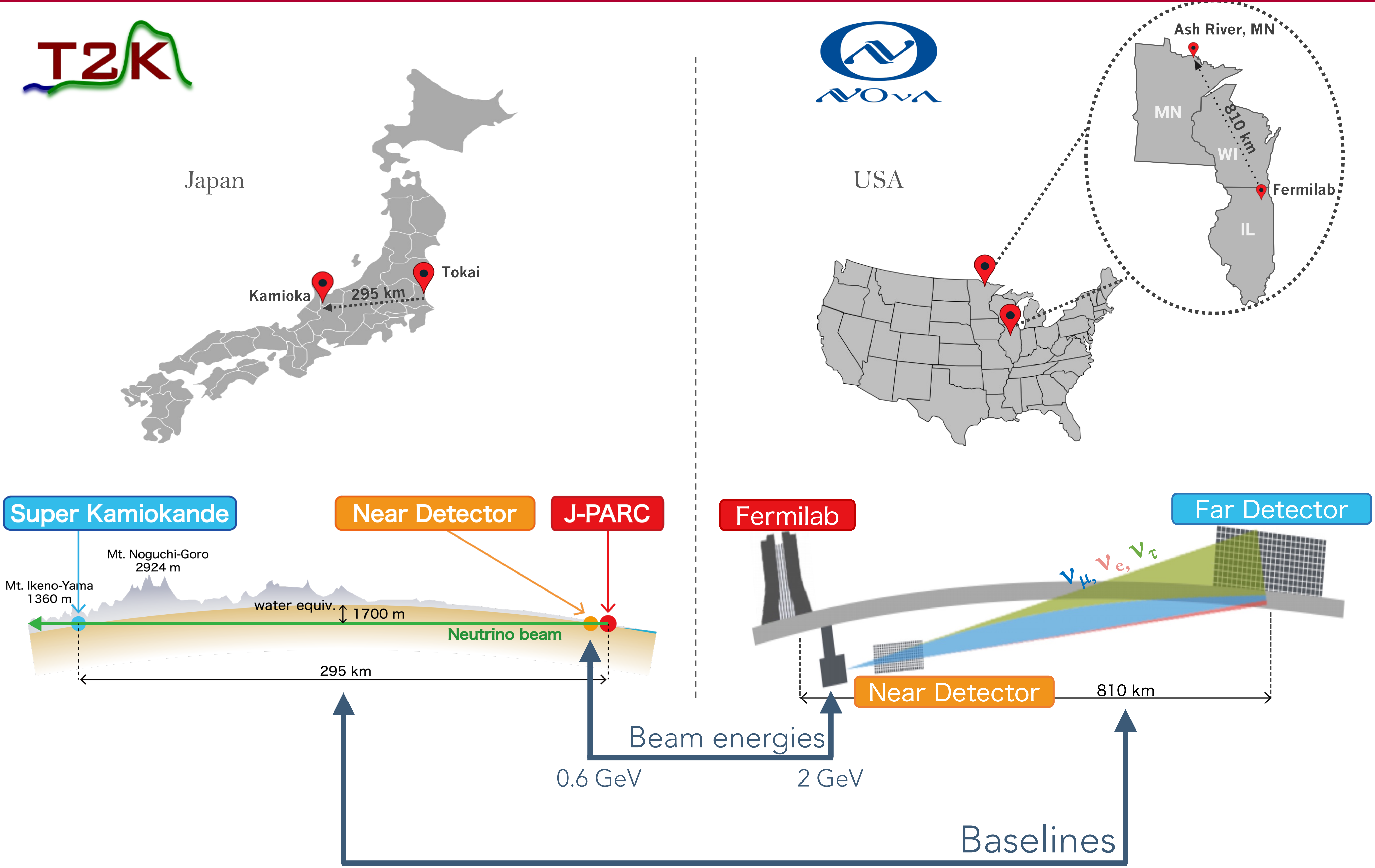
Combining Long-baseline Experiments



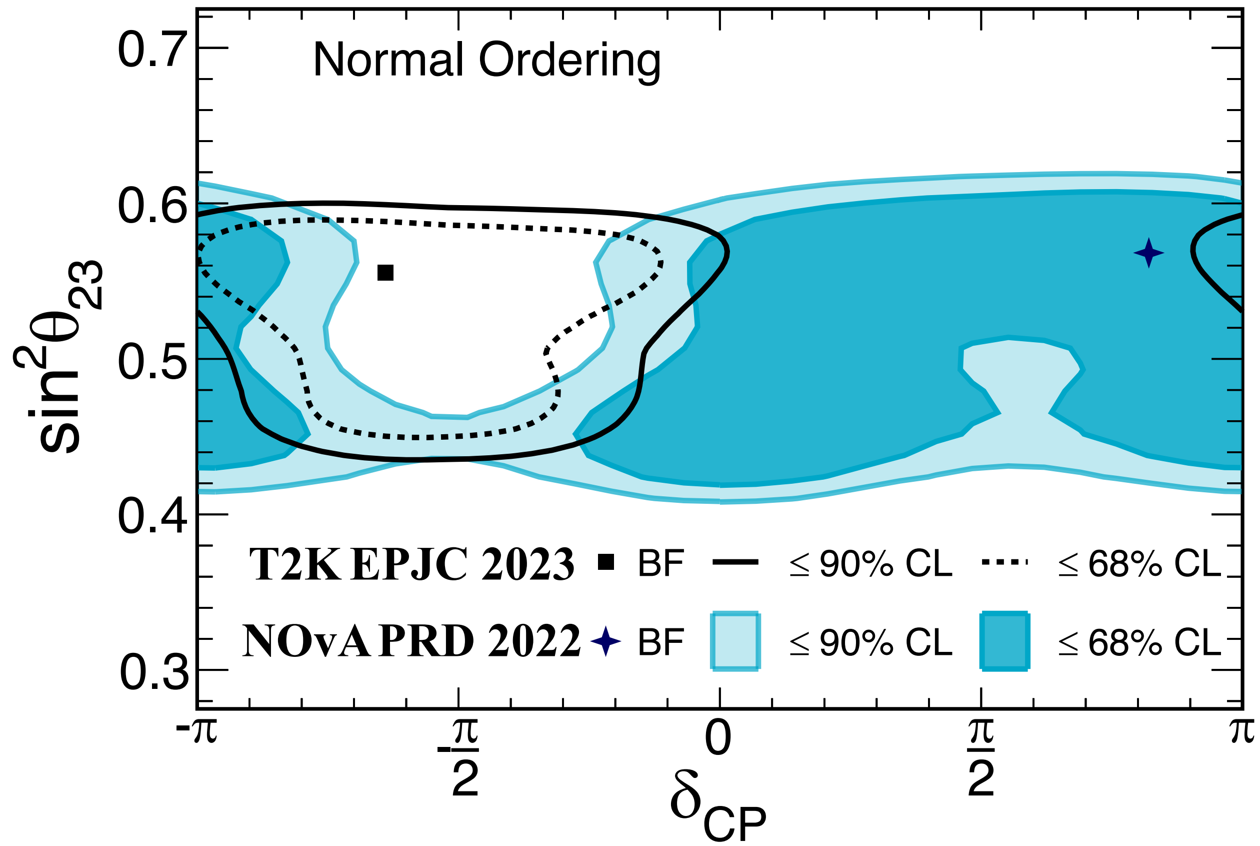


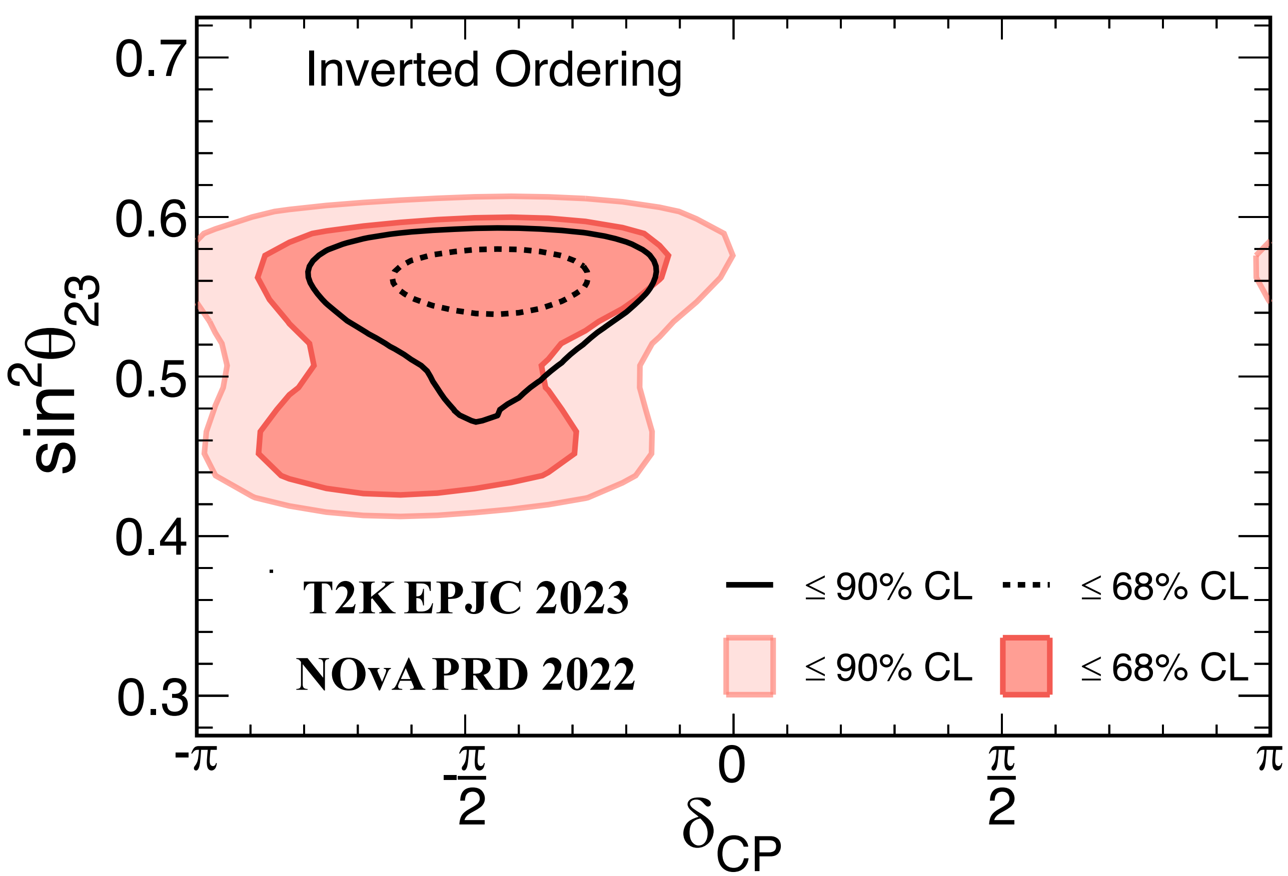
Combining Long-baseline Experiments



Why Combine T2K & NOvA?

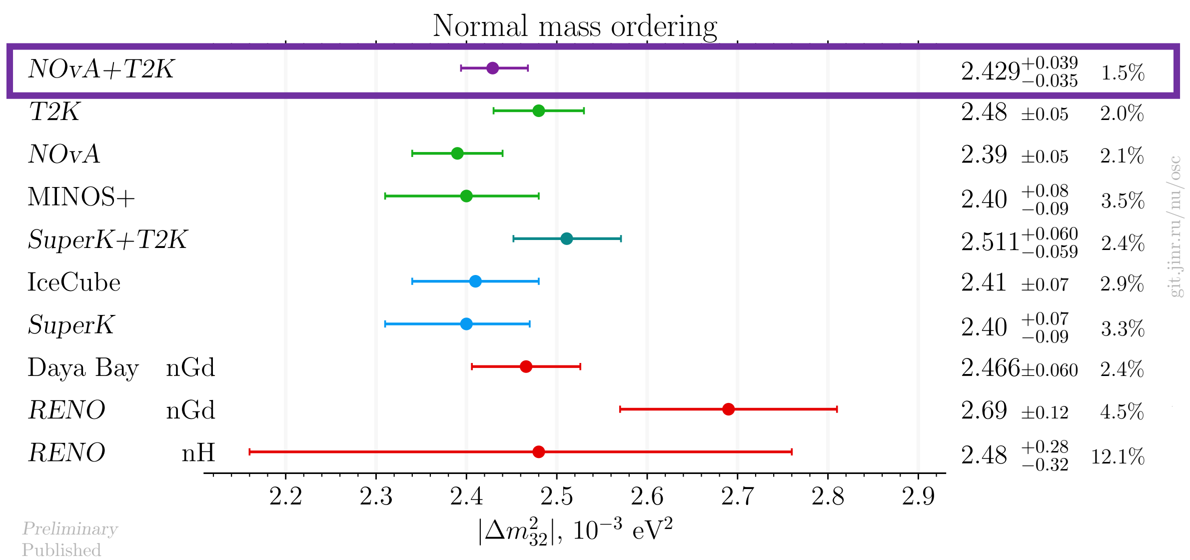
- Complementarity between the two experiments provides the power to **break degeneracies**.
  - Joint Analysis probes different oscillation environments, lifting degeneracies of individual experiments.
- In-depth review of:
  - Models, systematic uncertainties and possible correlations.
  - Different analysis approaches driven by contrasting detector design.
- Full implementation of:
  - Energy reconstruction and detector response of both experiments.
  - Combined detailed likelihood of both experiments.
  - Consistent statical inference across full dimensions of phase space.

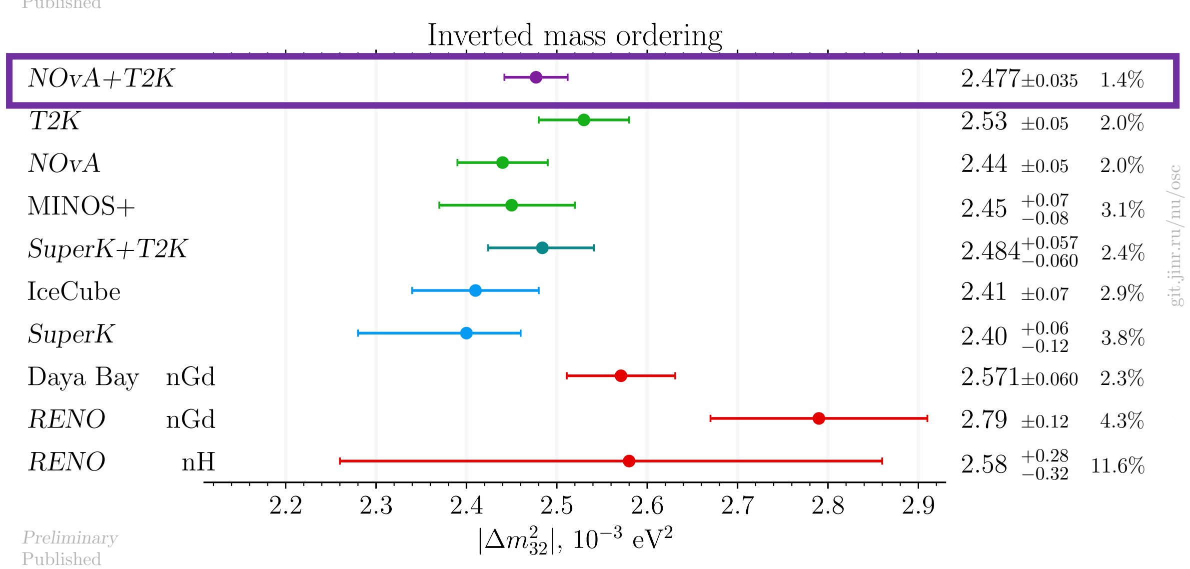


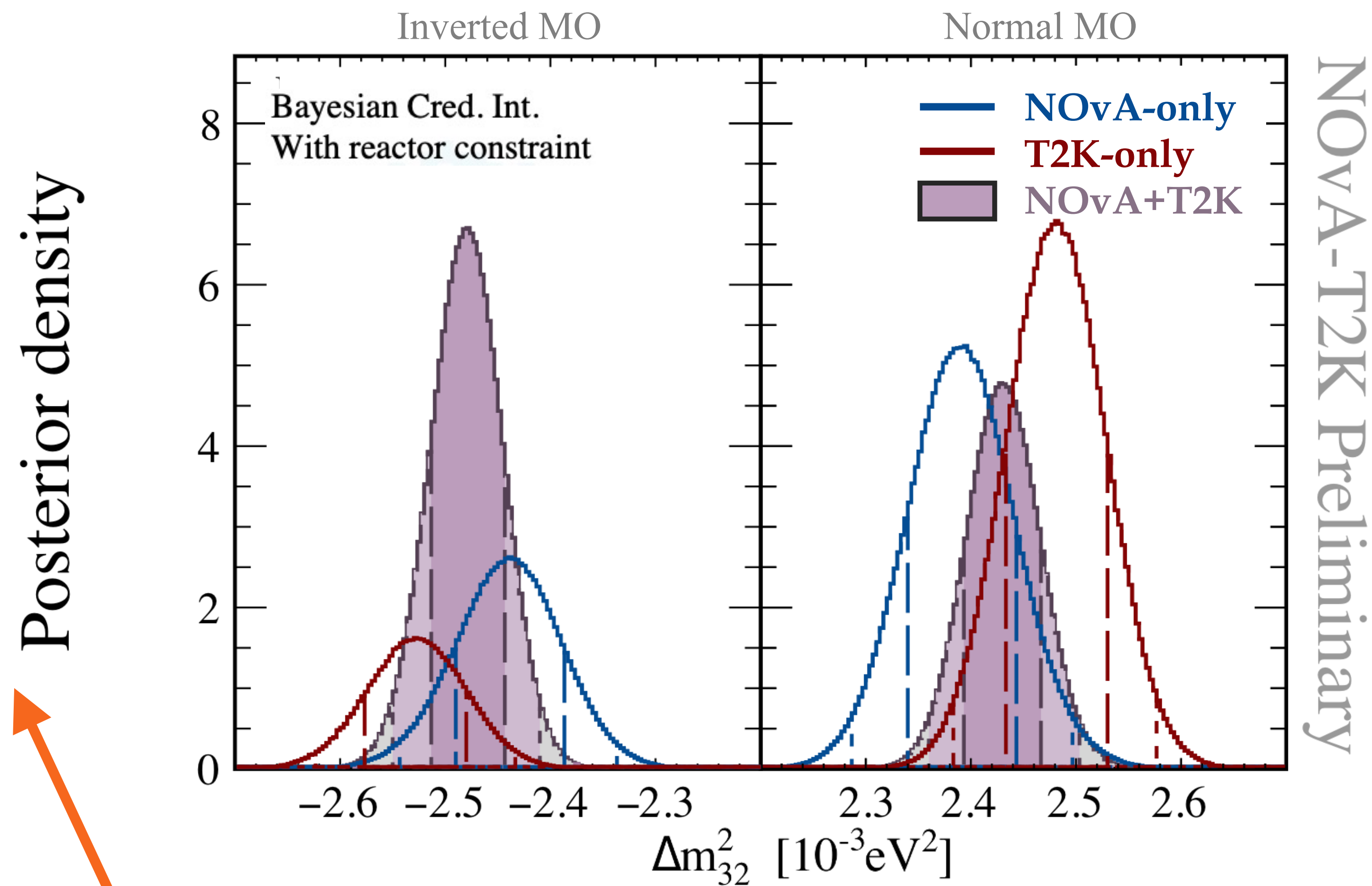


Δm^2_{32} & Mass Ordering

- Compare fraction of posterior density in each Mass Ordering.
- **Inverted ordering is weakly preferred** with a Bayes factor of 1.36 (IO/NO).







Smallest uncertainty on $|\Delta m^2_{32}|$ as compared to other previous measurements.

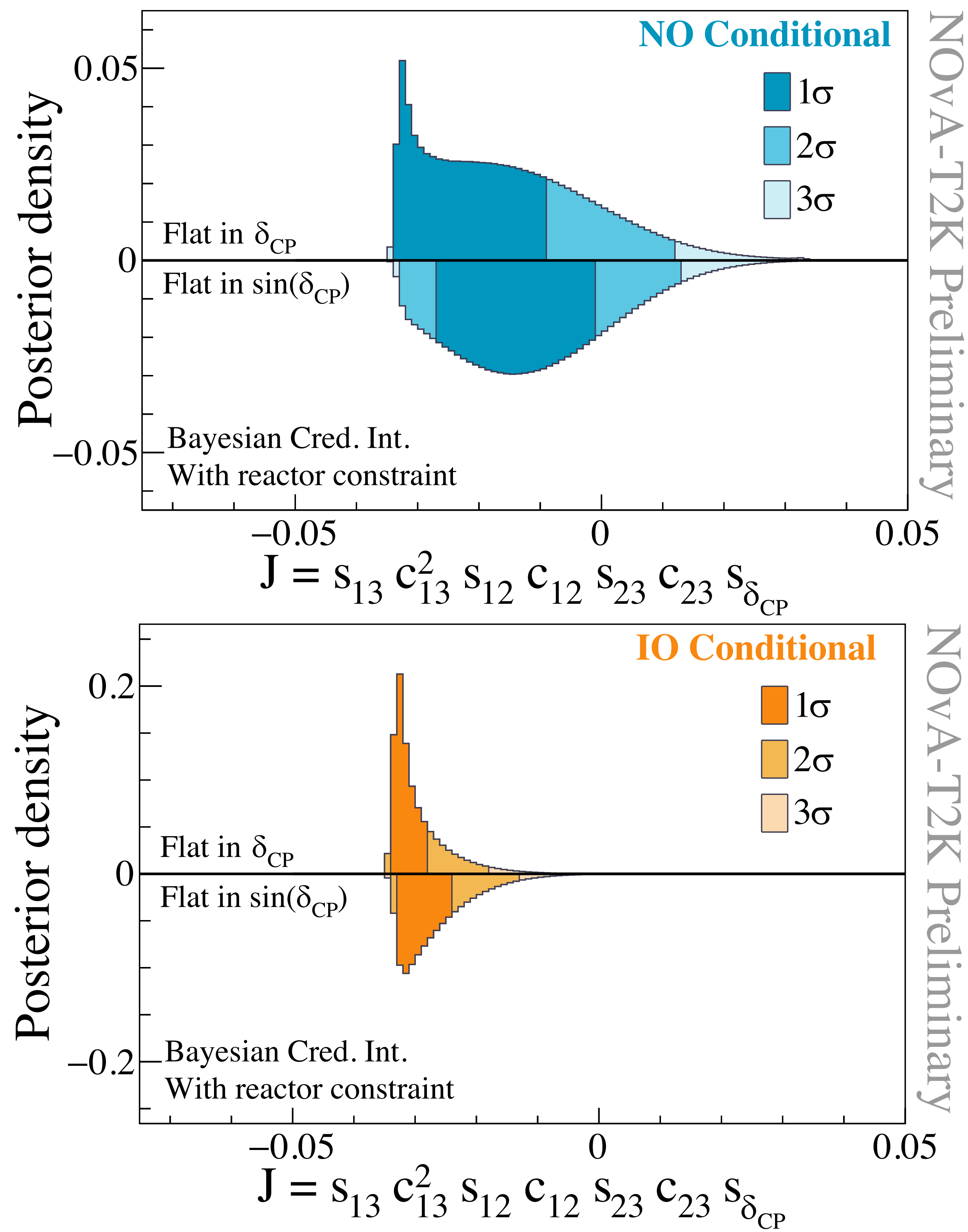
CP Violation

- Jarlskog-invariant is **parameterisation-independent*** way to measure CP violation.

$$J = \sin\theta_{13} cos^2\theta_{13} \sin\theta_{12} \cos\theta_{12} \sin\theta_{23} \cos\theta_{23} \sin\delta_{CP}$$

$$J = 0 : \text{CP conversed}, J \neq 0 : \text{CP Violation}$$

- $J = 0$ lies outside of the 3σ credible interval for the Inverted Ordering.
- For Normal Ordering, a considerably wider range of probable values for J.



*Phys. Rev. D 100, 053004 (2019)

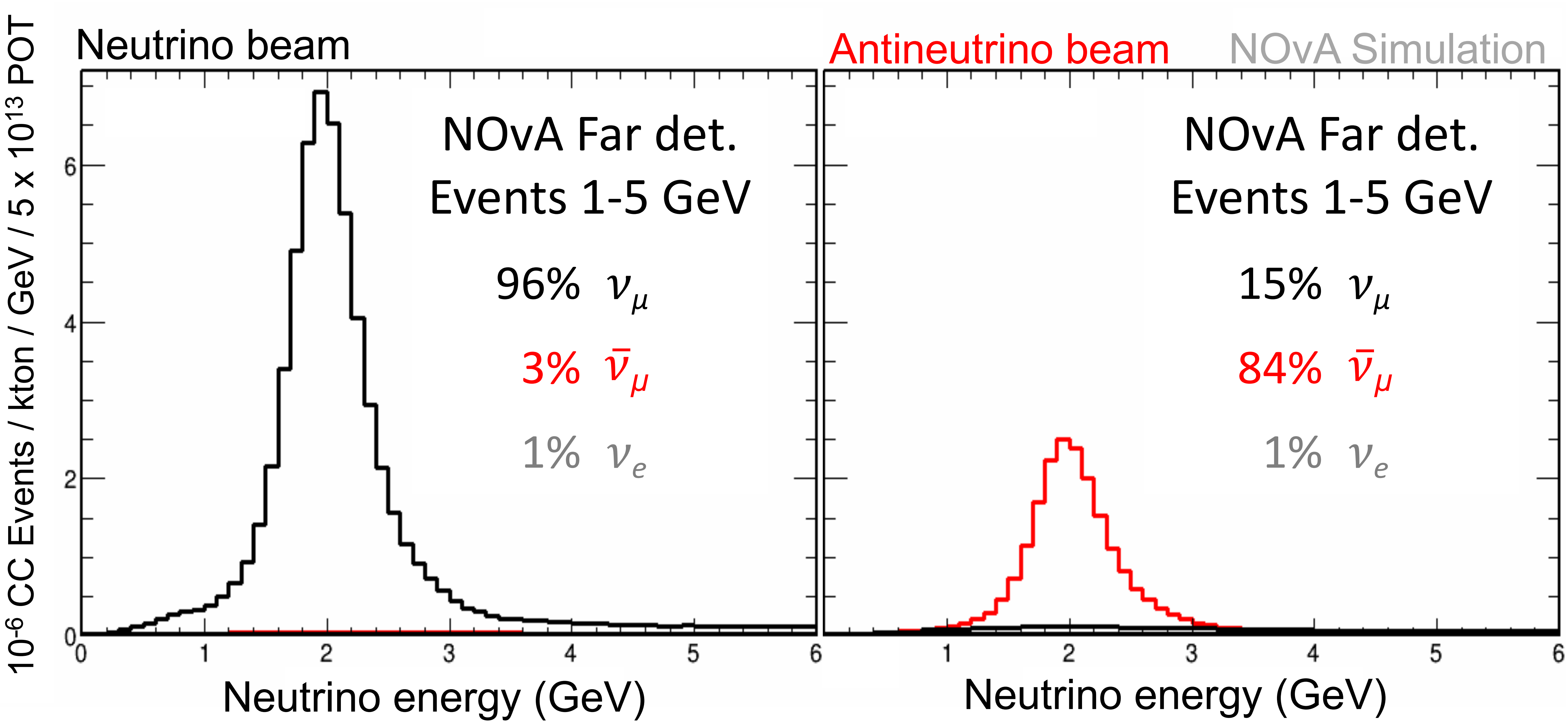
Summary

- NOvA has performed two new cross section measurements sensitive to MEC interactions.
  - Papers for both currently in internal review (targeting PRD).
- NOvA now has a second statistical treatment to probe 3 flavour oscillations.
  - Used it to reanalyse the "2020" dataset.
  - Enabled an independent measurement of θ_{13}, consistent with reactor experiments.
- NOvA and T2K have performed a joint fit of their neutrino data.
  - Smallest uncertainty on $|\Delta m^2_{32}|$ as compared to previous measurements.
  - A small preference for the Inverted Ordering shown.
  - Normal Ordering permits a wide range of permissible J, while the CP conserving value for the Inverted Ordering falls outside of the 3σ credible interval.
- NOvA and T2K are actively exploring the scope and timeline for the next steps to take this work forward!
- **Neutrino beam returns this month!**

NOvA In London, Summer 2023

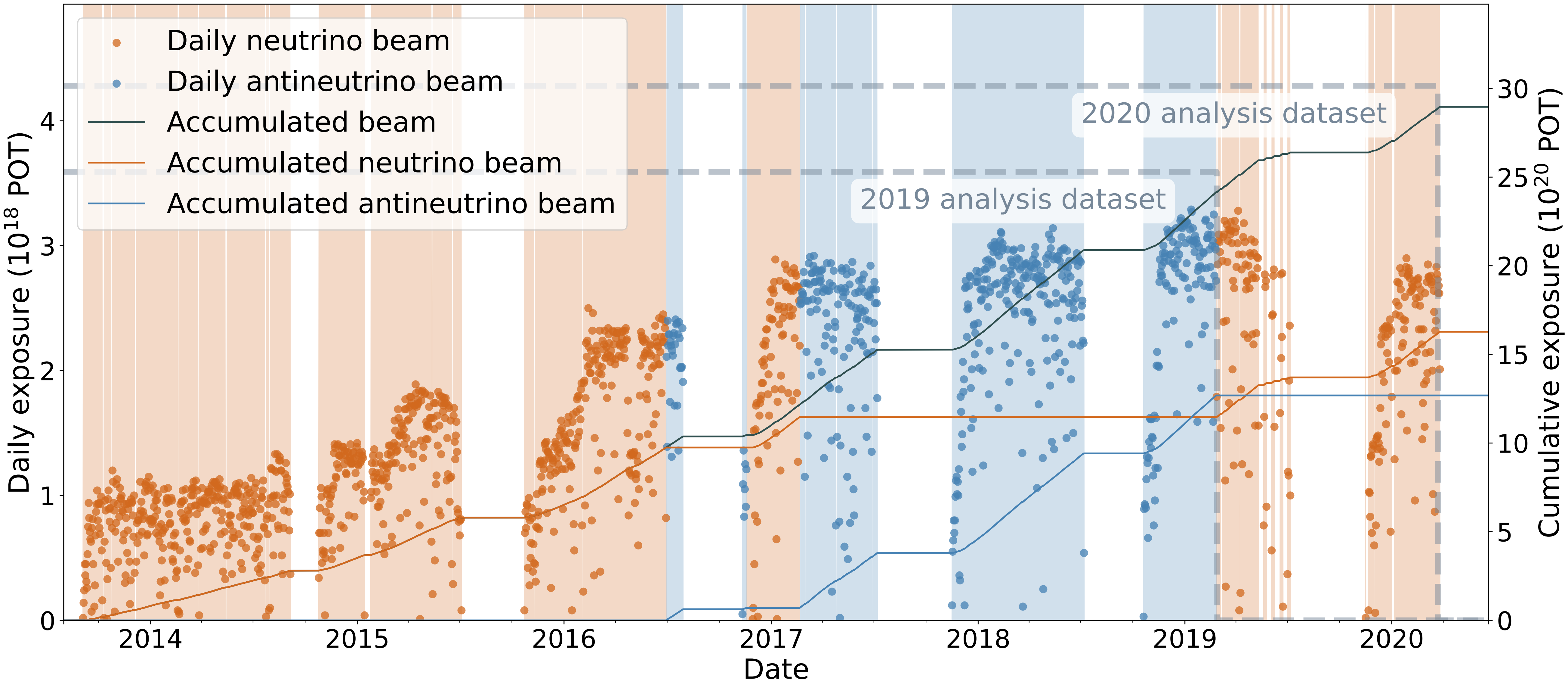
Back-up

NuMI Off-axis Narrow Band Beam

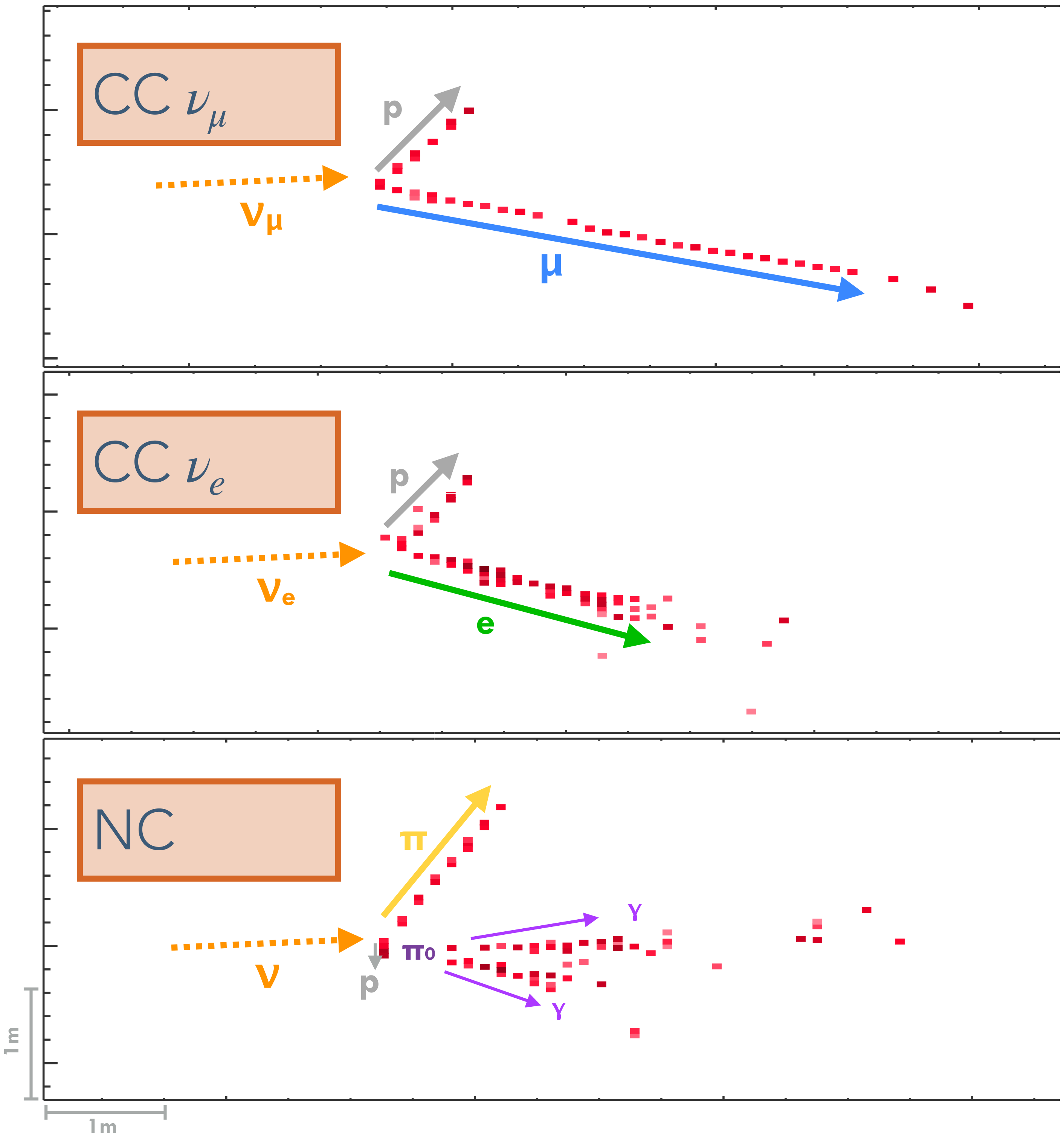


- Peak flux around 2 GeV.
- Neutrino or antineutrino modes.
- High ν_μ ($\bar{\nu}_\mu$) purity.
- Delivered ~ 40 x 10^{20} POT to date.

POT Collected Against Time

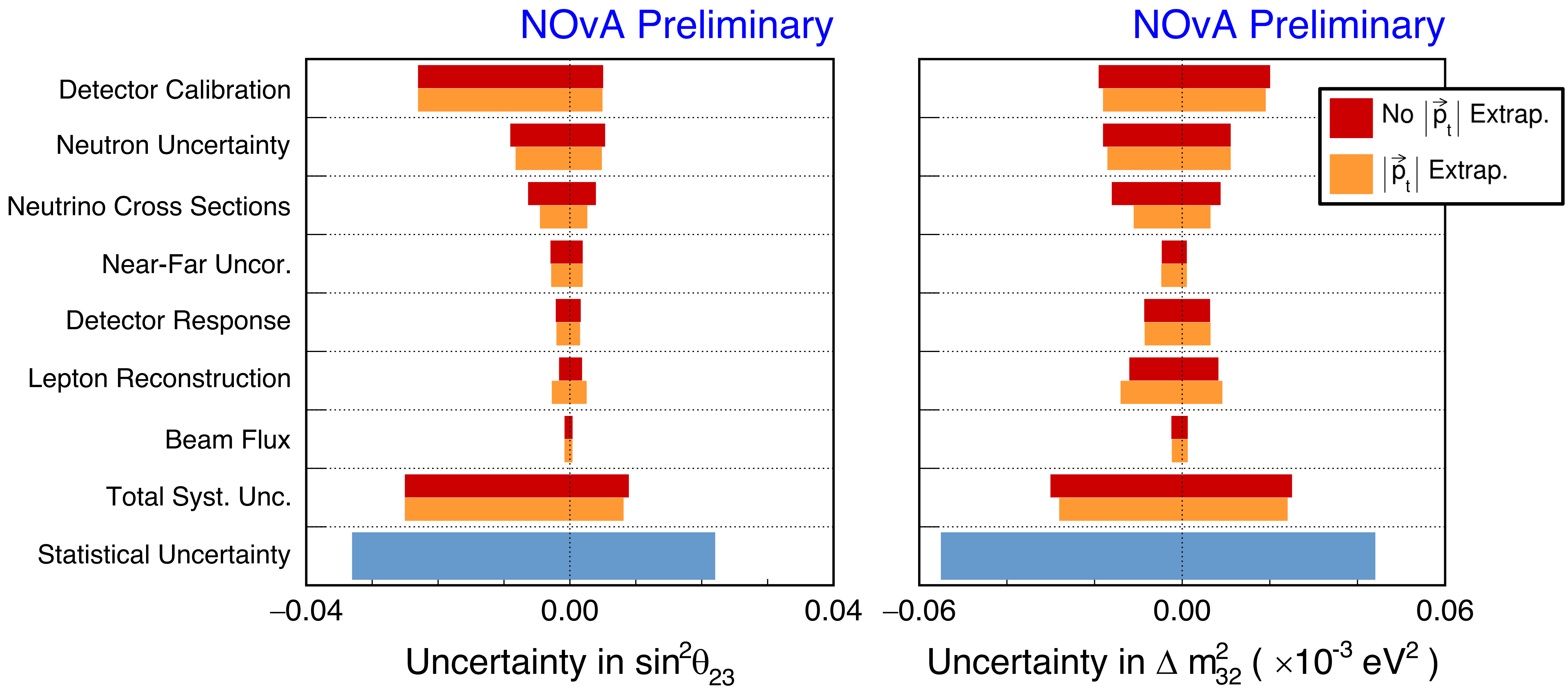


Selecting & Identifying Neutrinos



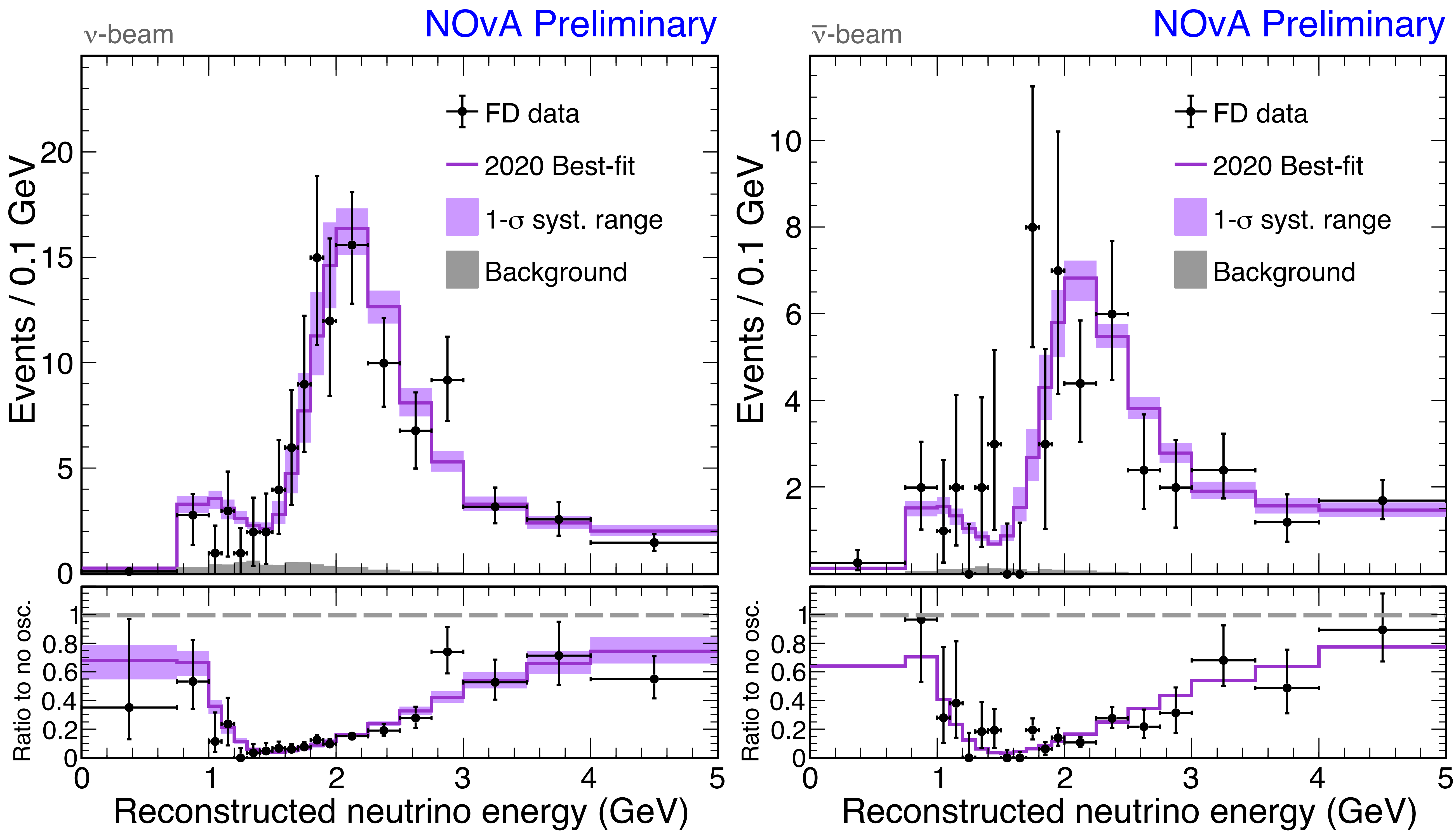
- Each type of neutrino event leaves a unique signature.
- Deep learning is used to aid with classification:
  - Cross section analyses use it to identify **single particles**.
  - Oscillation analyses use a convolution visual network to identify **whole events**.

Systematic Uncertainties with p_t Extrapolation



- Overall systematic reduction is 5-10%.
- 30% reduction in cross-section uncertainties.
  - Reduces the size of systematics most likely to contain "unknown unknowns."
  - Slight increase in systematics on lepton reconstruction.

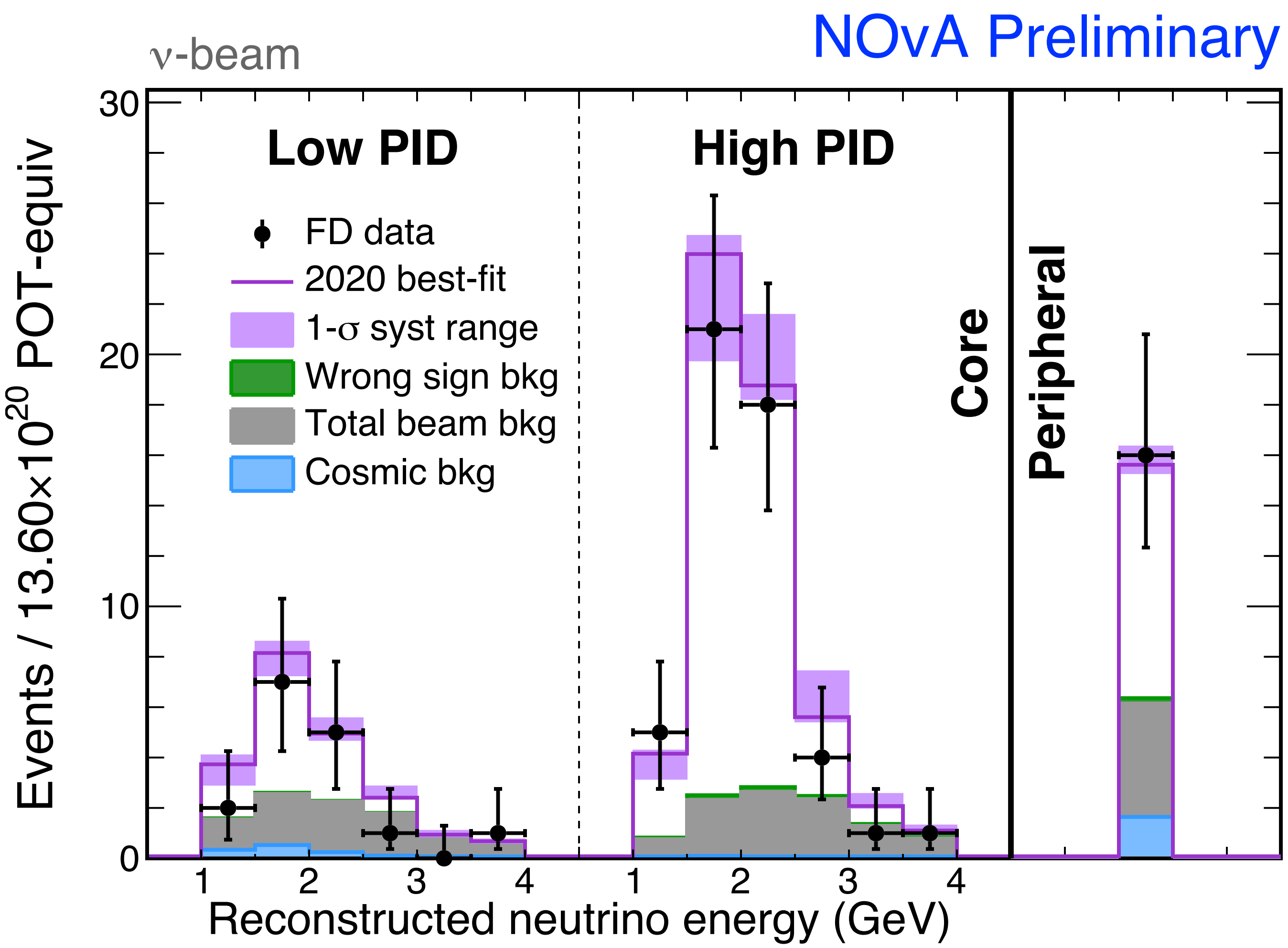
ν_μ and $\bar{\nu}_\mu$ Data at the Far Detector

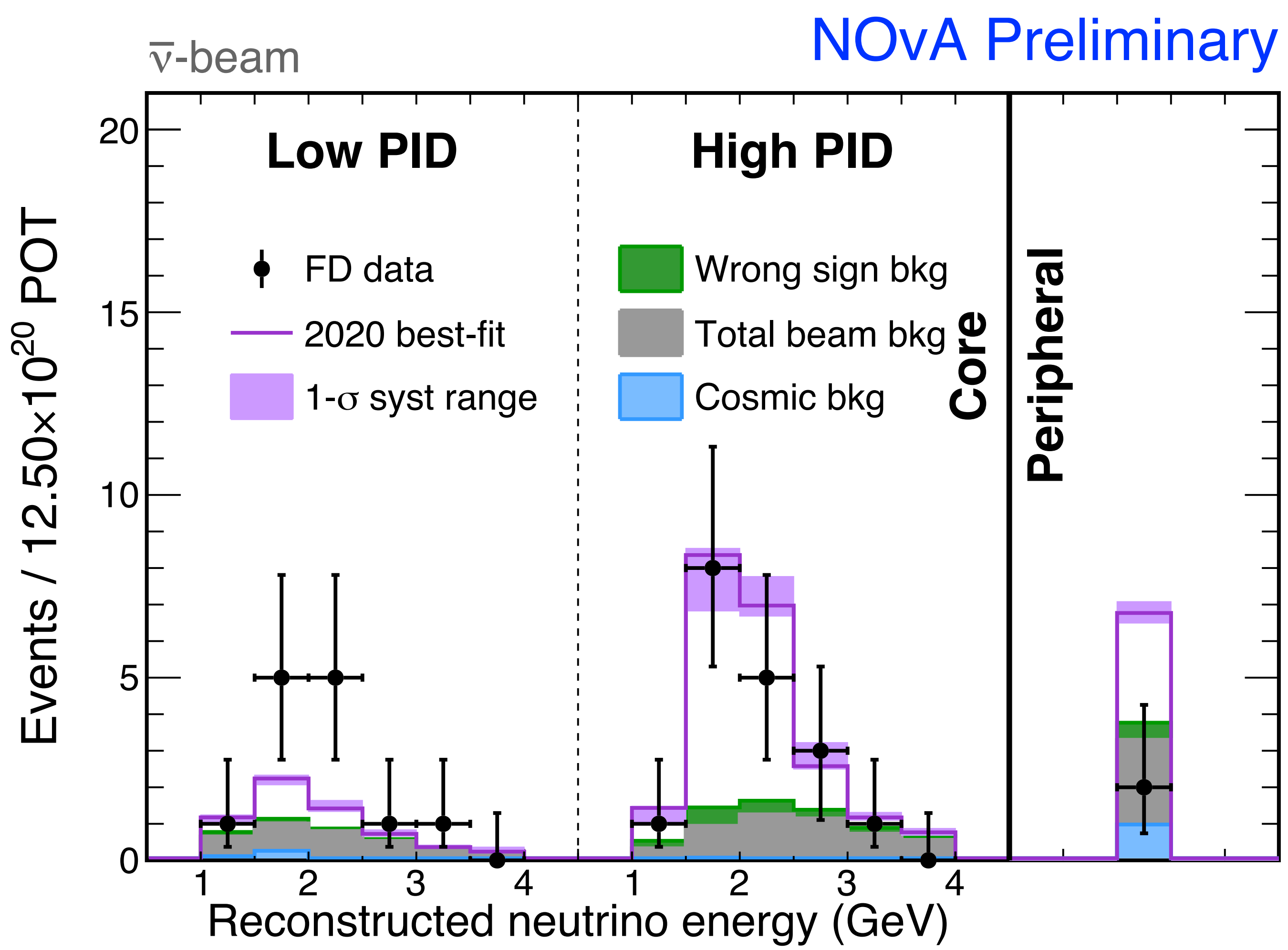


211 events, 8.2 background

105 events, 2.1 background

ν_e and $\bar{\nu}_e$ Data at the Far Detector



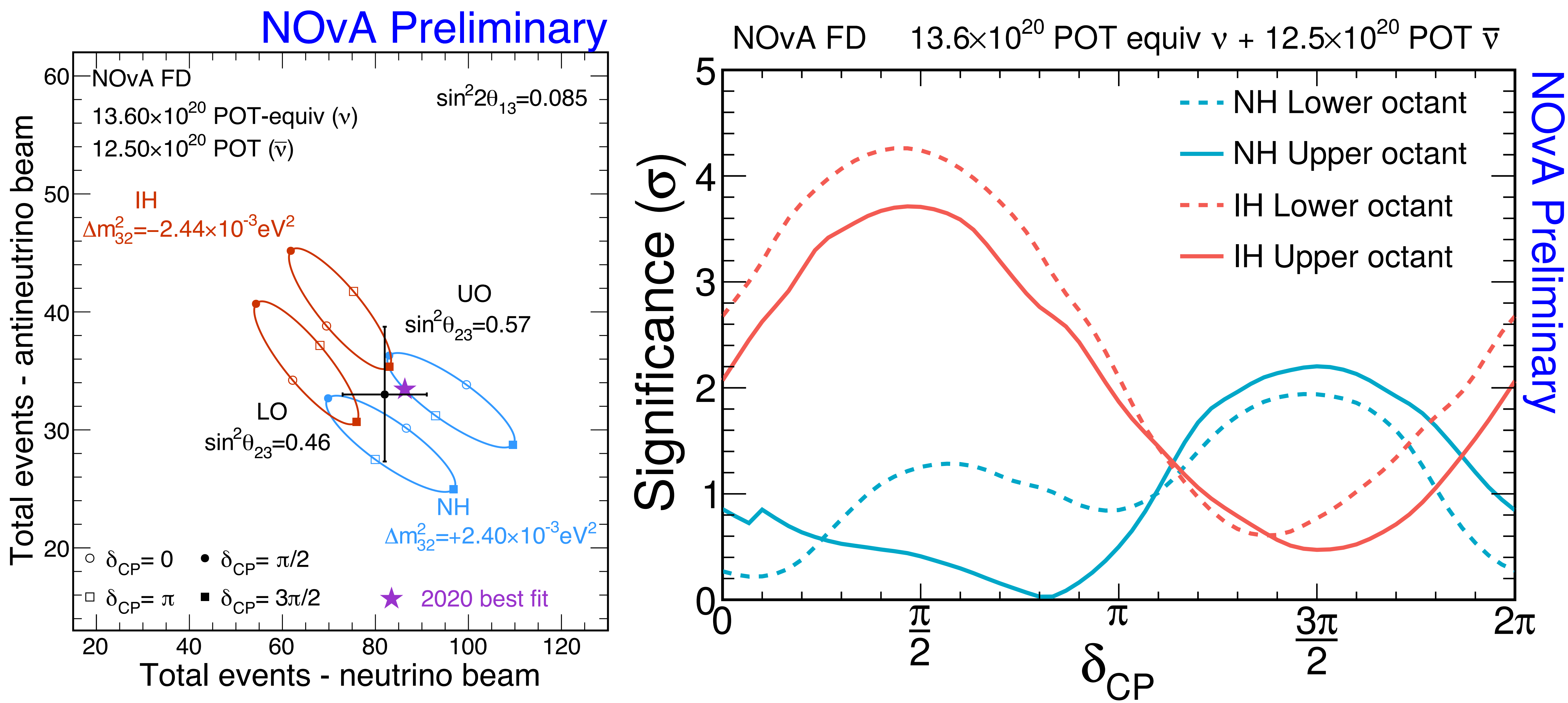


Total Observed	82	Range
Total Prediction	85.8	52-110
Wrong-sign	1.0	0.6-1.7
Beam Bkgd.	22.7	
Cosmic Bkgd.	3.1	
Total Bkgd.	26.8	26-28

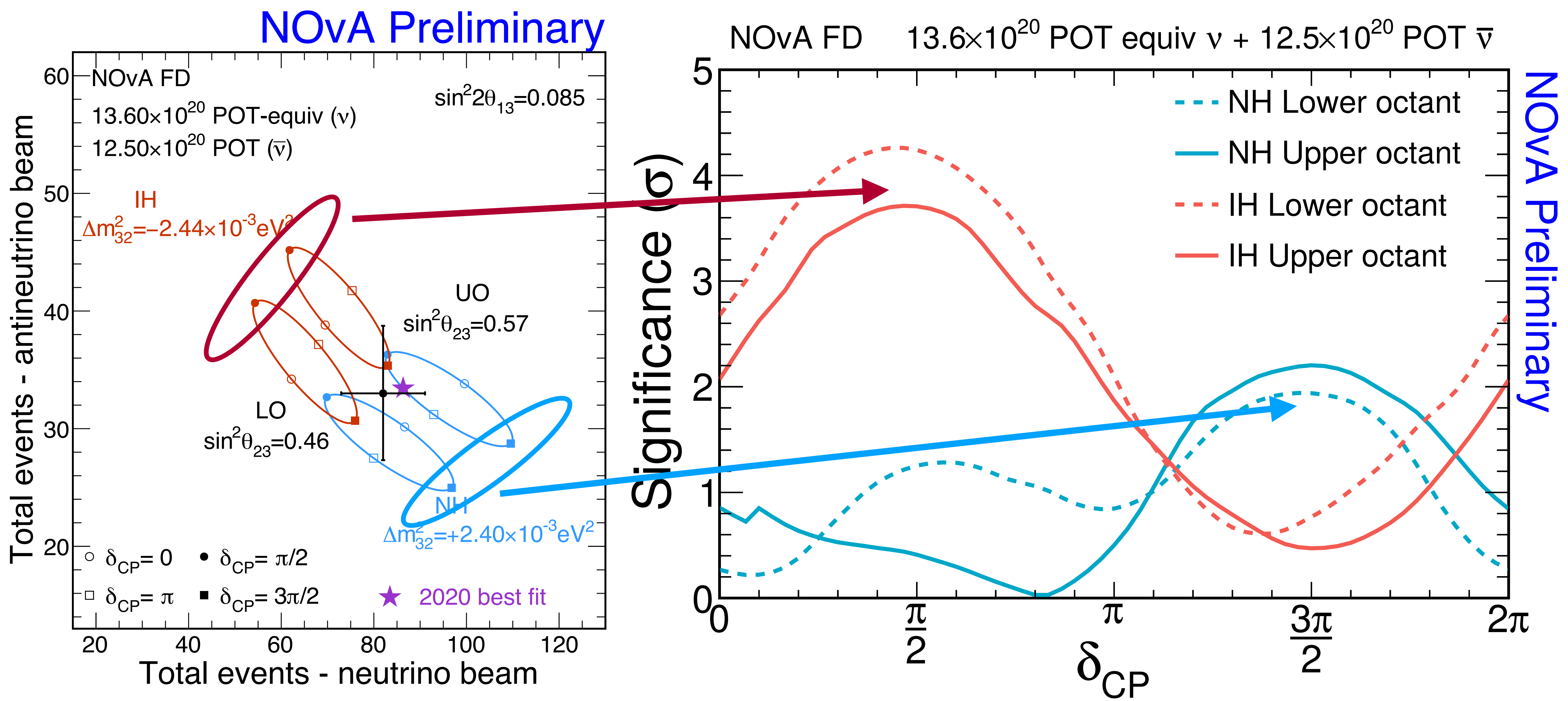
Total Observed	33	Range
Total Prediction	33.2	25-45
Wrong-sign	2.3	1.0-3.2
Beam Bkgd.	10.2	
Cosmic Bkgd.	1.6	
Total Bkgd.	14.0	13-15

$>4\sigma$ of $\bar{\nu}_e$ appearance

δ_{CP}



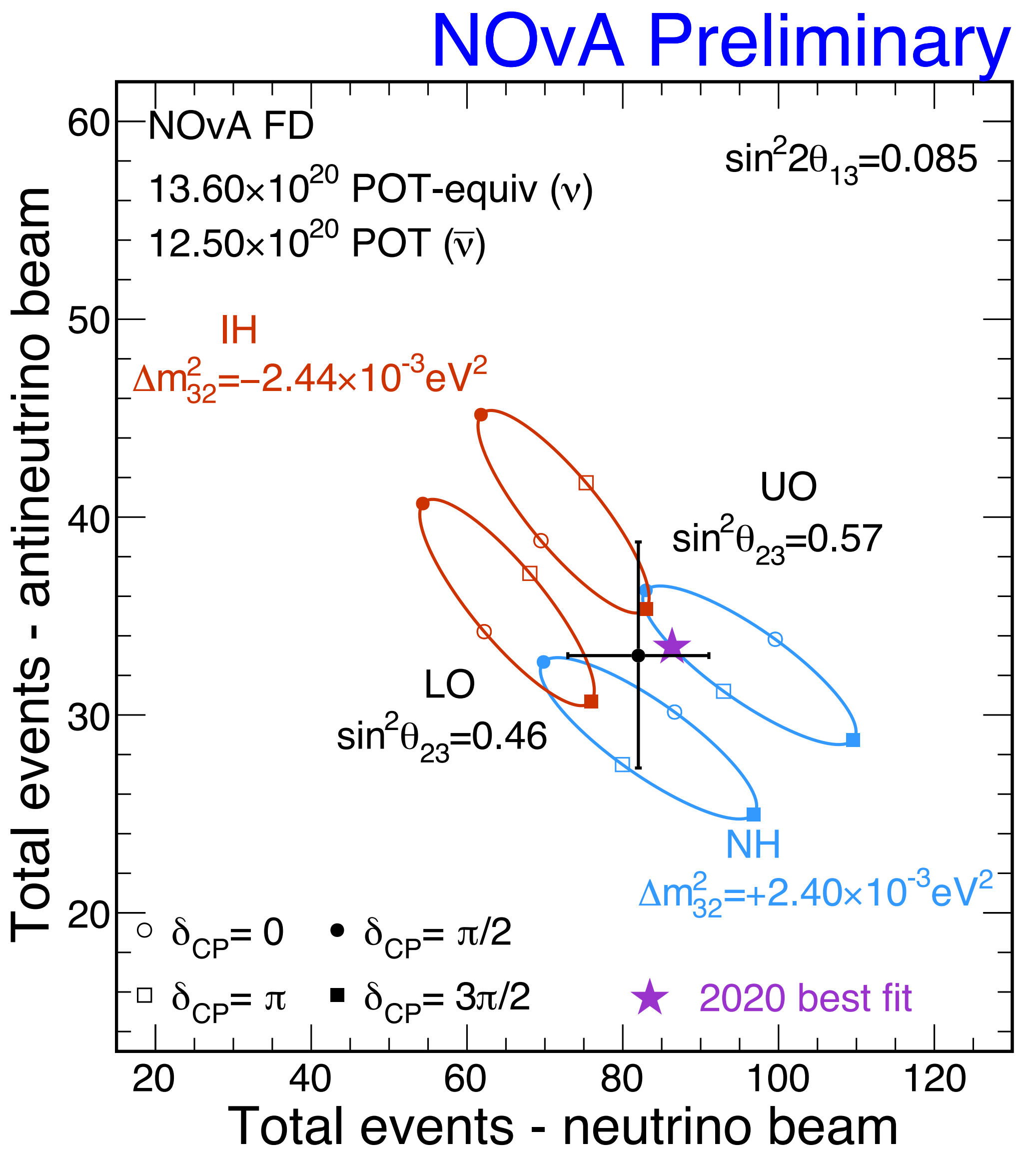
- No strong asymmetry in the rates of appearance of ν_e and $\bar{\nu}_e$.

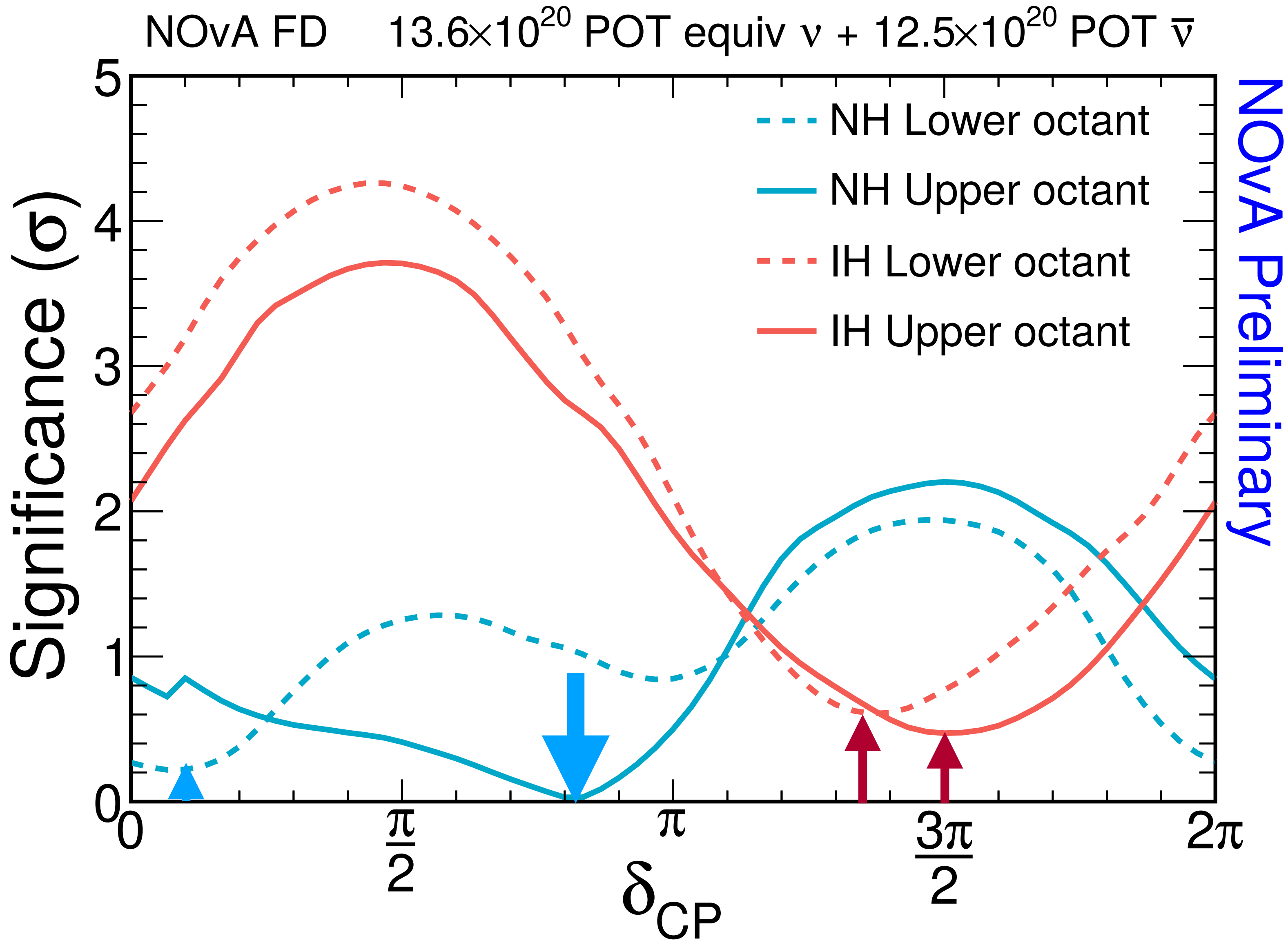


- No strong asymmetry in the rates of appearance of ν_e and $\bar{\nu}_e$.
- Disfavour hierarchy-δ_{CP} combinations which would produce asymmetry.

Exclude IH $\delta_{CP} = \frac{\pi}{2}$ at $> 3\sigma$

Disfavour NH $\delta_{CP} = \frac{3\pi}{2}$ at $\sim 2\sigma$





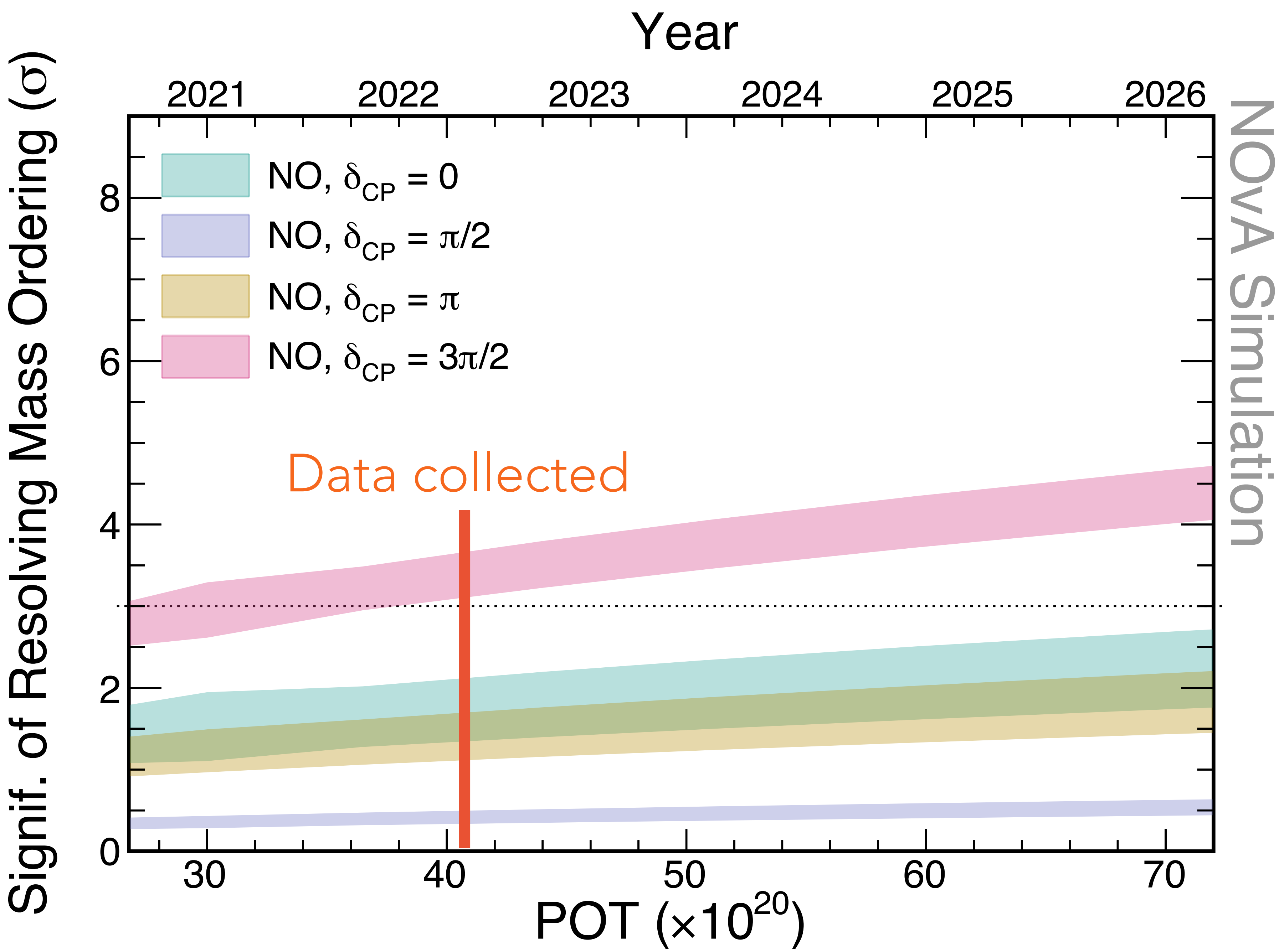
- No strong asymmetry in the rates of appearance of ν_e and $\bar{\nu}_e$.
- Disfavour hierarchy-δ_{CP} combinations which would produce asymmetry.

Prefer:

Normal Hierarchy at 1σ

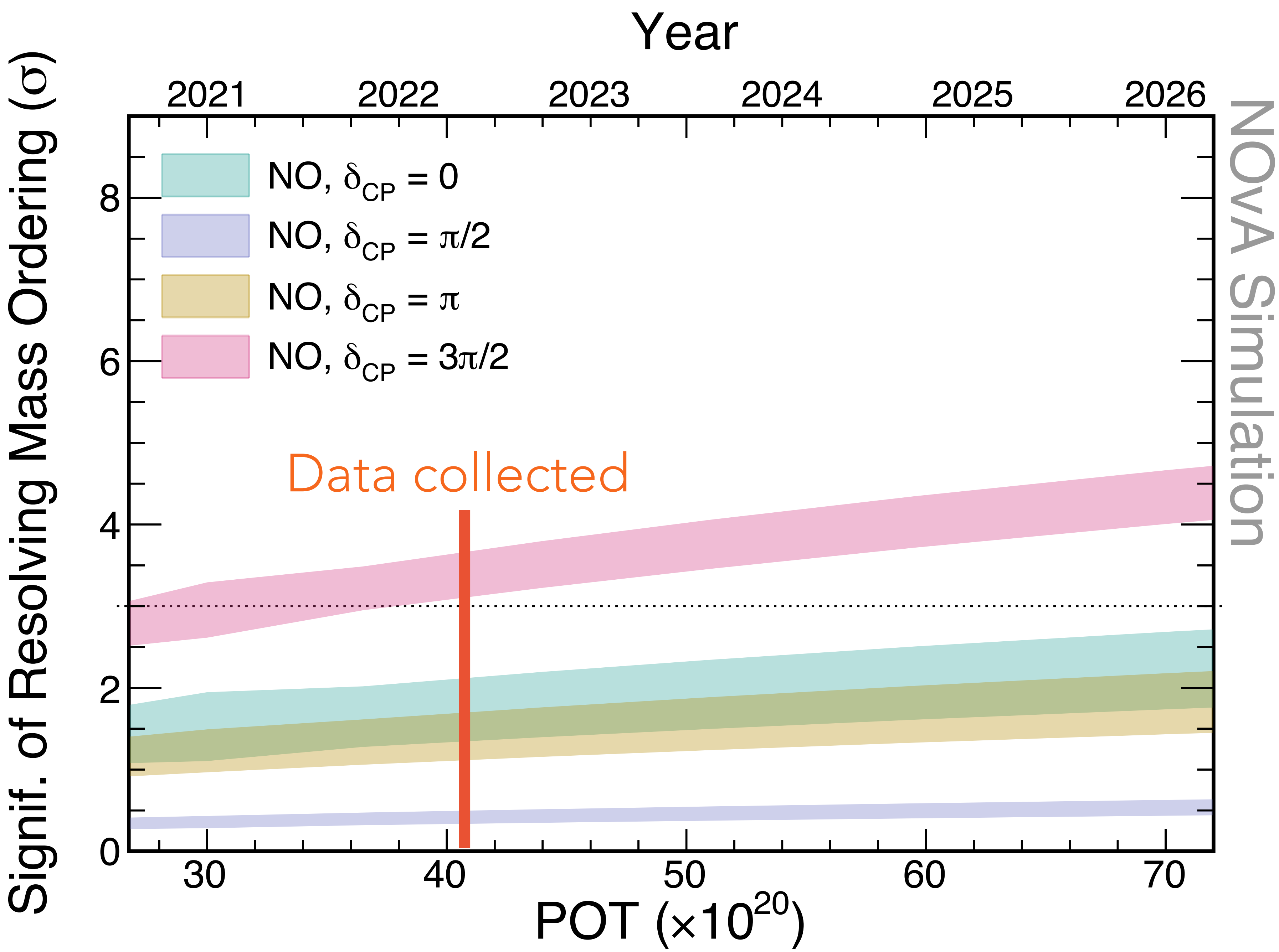
Upper Octant at 1.2σ

Future Prospects



- Increasing sensitivity to the mass ordering to come, will more than double the dataset in both beam modes.
- Greater than 3 σ mass ordering sensitivity for 30 - 40% of δ_{CP} values.

Future Prospects



Models & Systematics

Challenge: Decide what common physics parameters the two experiments have, should they be correlated and by how much.

Flux Model

- Different energies
- Different tuning to external data
  - thin target vs thick target data
- Enters the analysis differently

❑ No significant correlations between the experiments

Detector Model

- Different detector design and targets
- Different selections
  - inclusive vs exclusive outgoing pions
- Different energy reconstruction
  - calorimetric vs lepton kinematics

❑ No significant correlations between the experiments

Cross Section Model

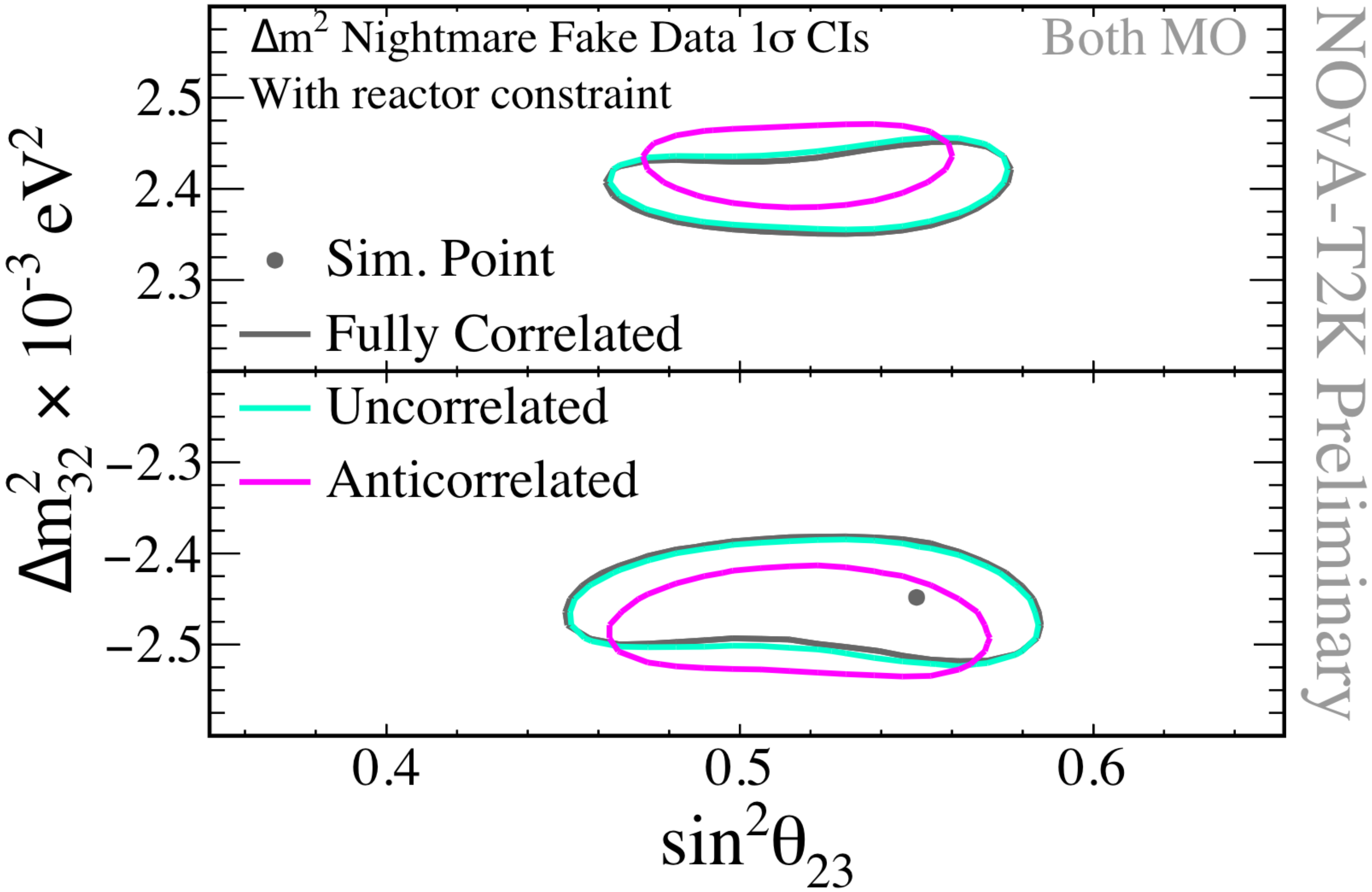
- As the underlying physics is fundamentally the same, we expect correlations
- Different neutrino interaction models
  - optimized for different energy ranges
- Systematics are designed for individual models and analysis strategies

❑ Impact of correlations is negligible on the results at the current statistical significance.

❑ Merits continued investigations for higher data exposures.

Z. Vallari

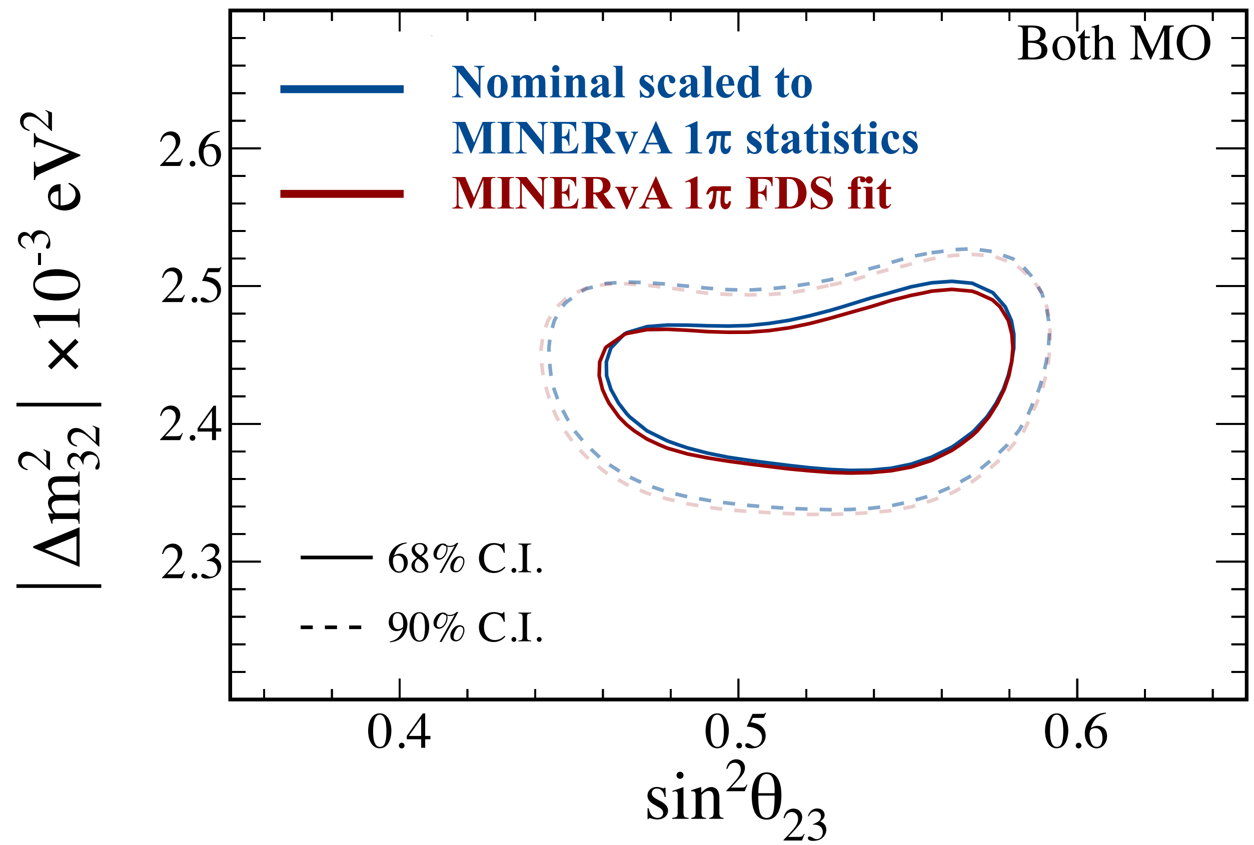
Studying Correlations

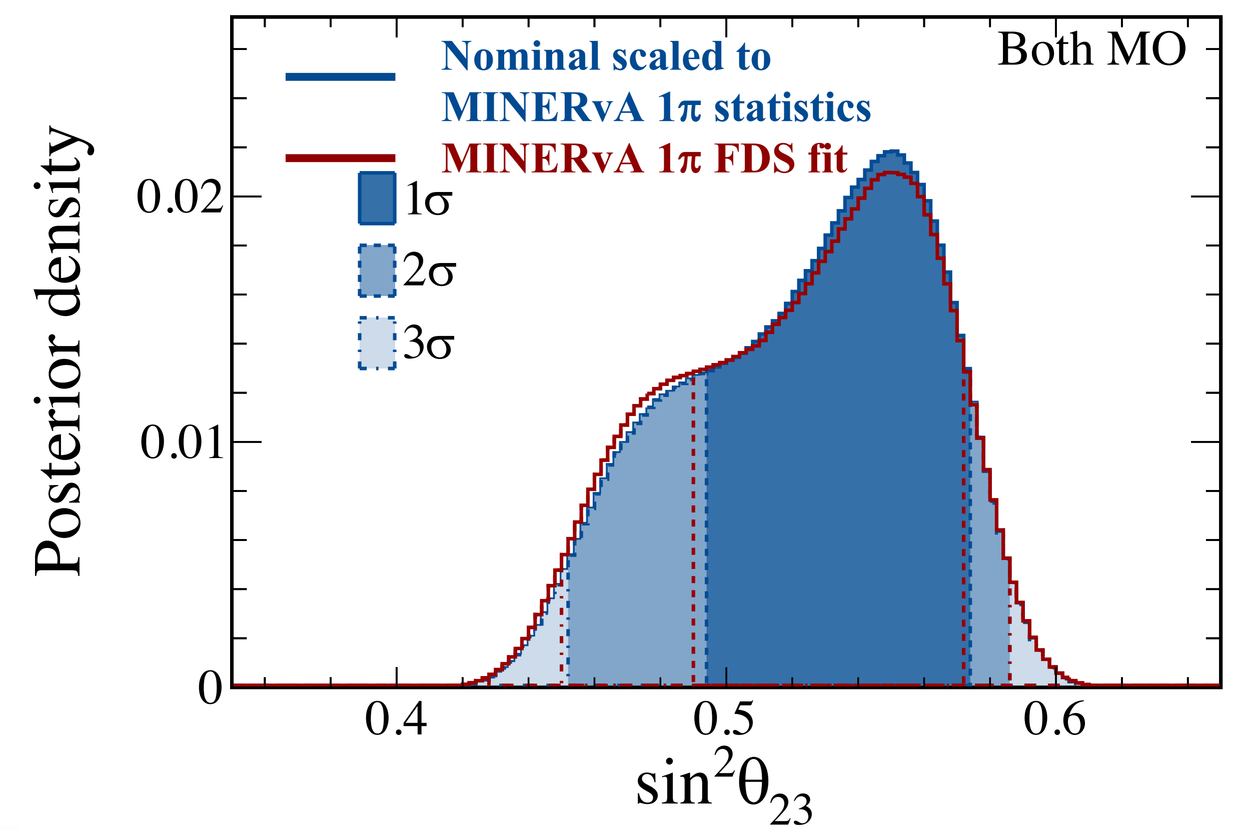


- **Strategy:** evaluate a range of artificial scenarios to asses the impact of possible correlations:
  - E.g, fabricate parameters for each experiment which should have significant bias on Δm^2_{32} and $\sin^2\theta_{23}$ (size of uncertainty comparable to the statistical uncertainty).
  - Study the impact of fully correlating, uncorrelating and fully anti-correlating these parameters.
  - Uncorrelated and correctly correlated (full correlation) credible intervals agree very well while incorrectly correlating systematics shows a bias -> leaving systematics like these uncorrelated wouldn't have a significant impact in the analysis.

Studying Alternate Models

- Ensure analysis is robust to **alternate neutrino interaction models**.
  - Generate **mock data** by changing part of simulation to use an alternative model.
  - Fit these mock datasets and check impact on oscillation results.
- Pre-decided thresholds for bias:
  - **Change in width** of 1D intervals should be no larger than **10%**.
  - **Change in central value** should be no larger than **50% of systemic uncertainty.**
- Investigated a range of alternative models at different oscillation points.
  - Example: suppression in single pion channel seen in MINERvA results*.
  - **No alternative model test failed the pre-set threshold for bias.**

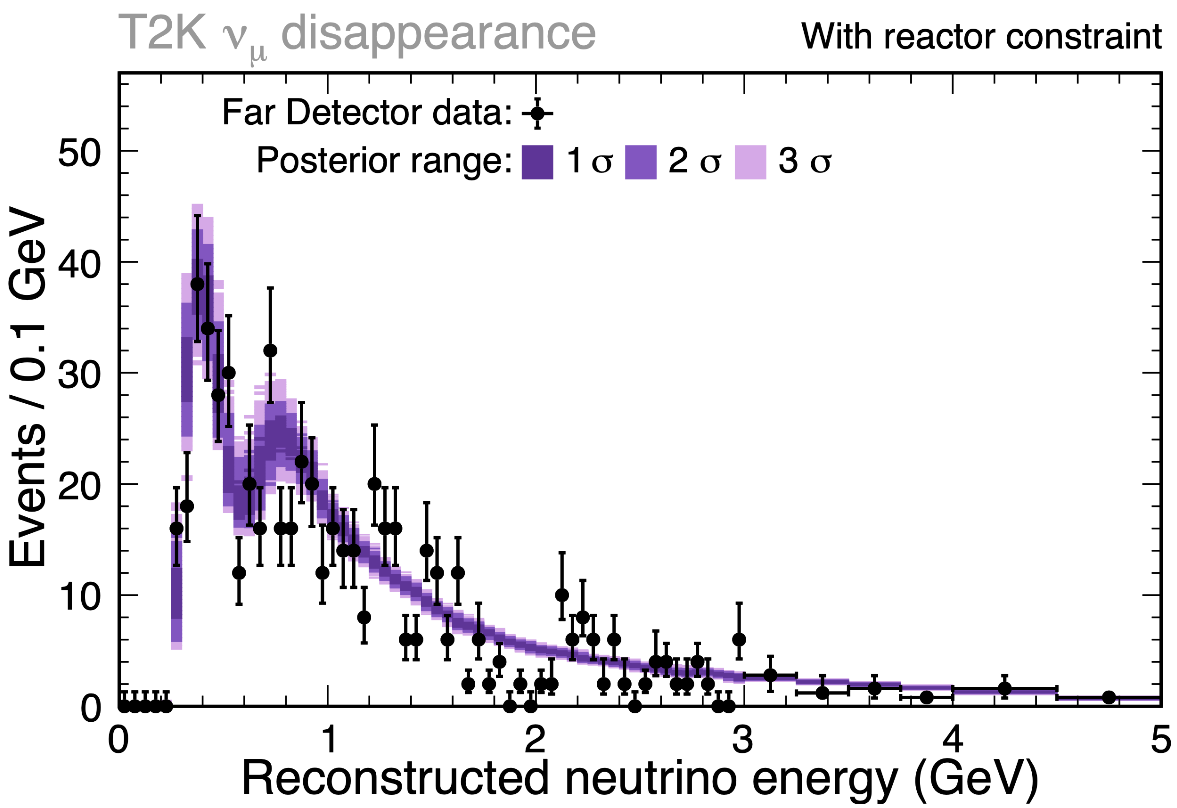


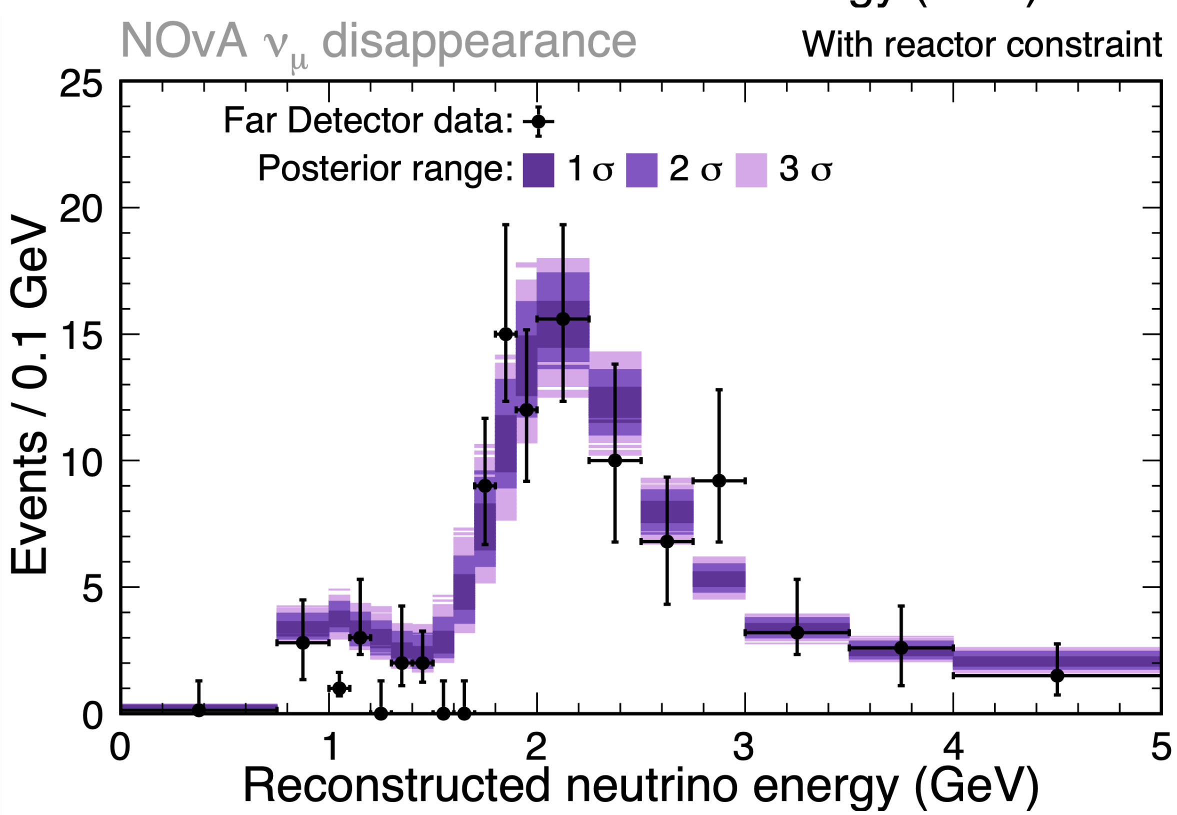


*Phys. Rev. D 100, 072005 (2019)

FD Data Samples

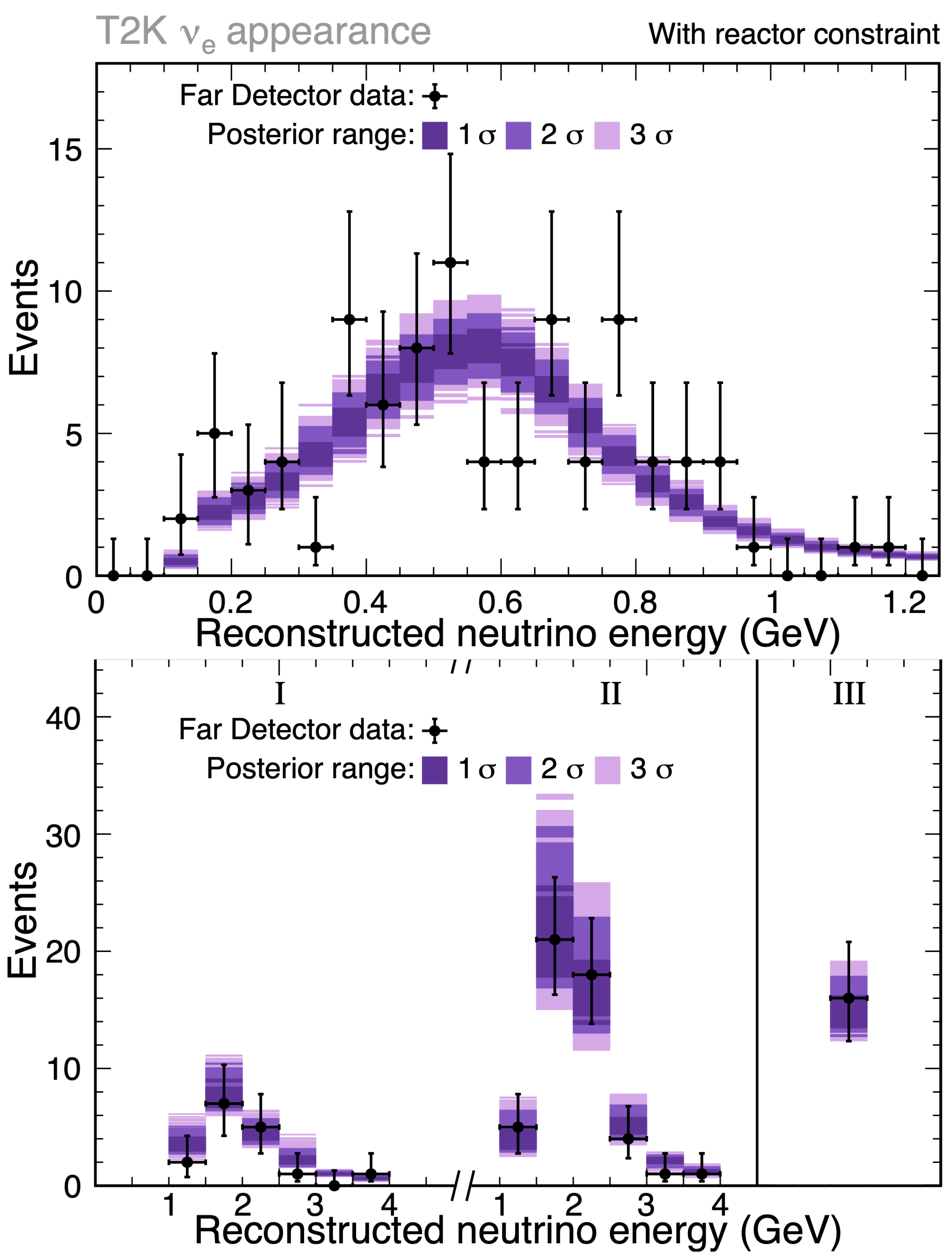
Channel	NOvA	T2K	Combined
ν_e	82	94 (ν_e) 14 ($\nu_e 1\pi$)	190
$\bar{\nu}_e$	33	16	49
ν_μ	211	318	529
$\bar{\nu}_\mu$	105	137	242
Total	431	579	1010





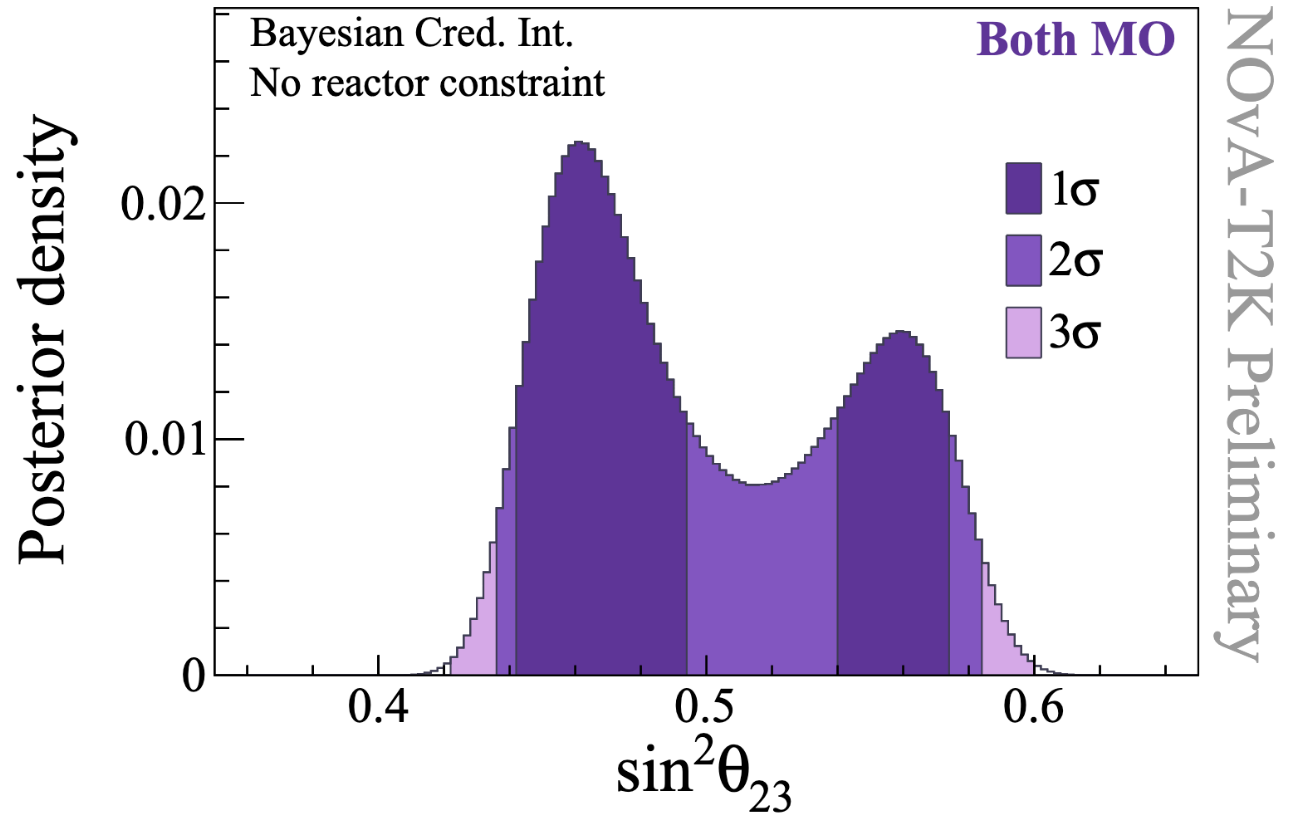
FD Data Samples

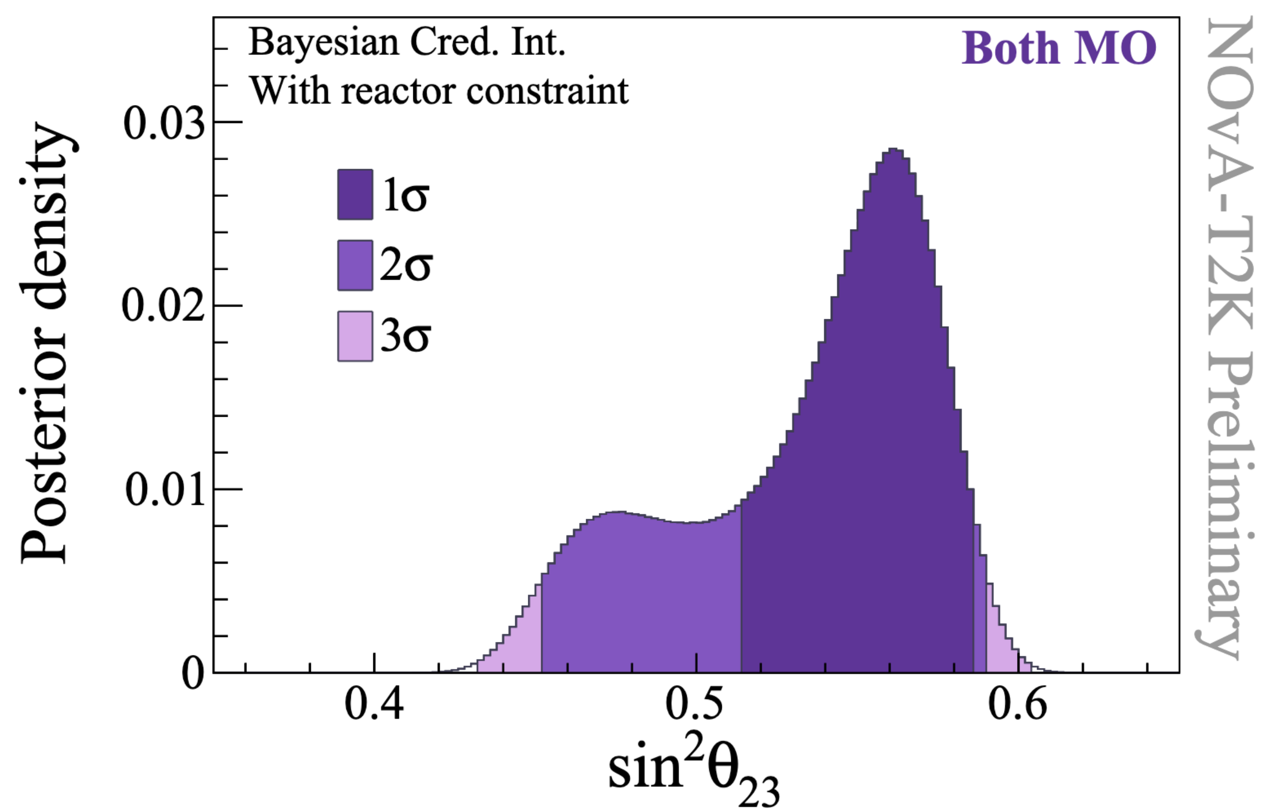
Channel	NOvA	T2K	Combined
ν_e	0.90	0.19 (ν_e) 0.79 ($\nu_e 1\pi$)	0.62
$\bar{\nu}_e$	0.21	0.67	0.40
ν_μ	0.68	0.48	0.62
$\bar{\nu}_\mu$	0.38	0.87	0.72
Total	0.64	0.72	0.75



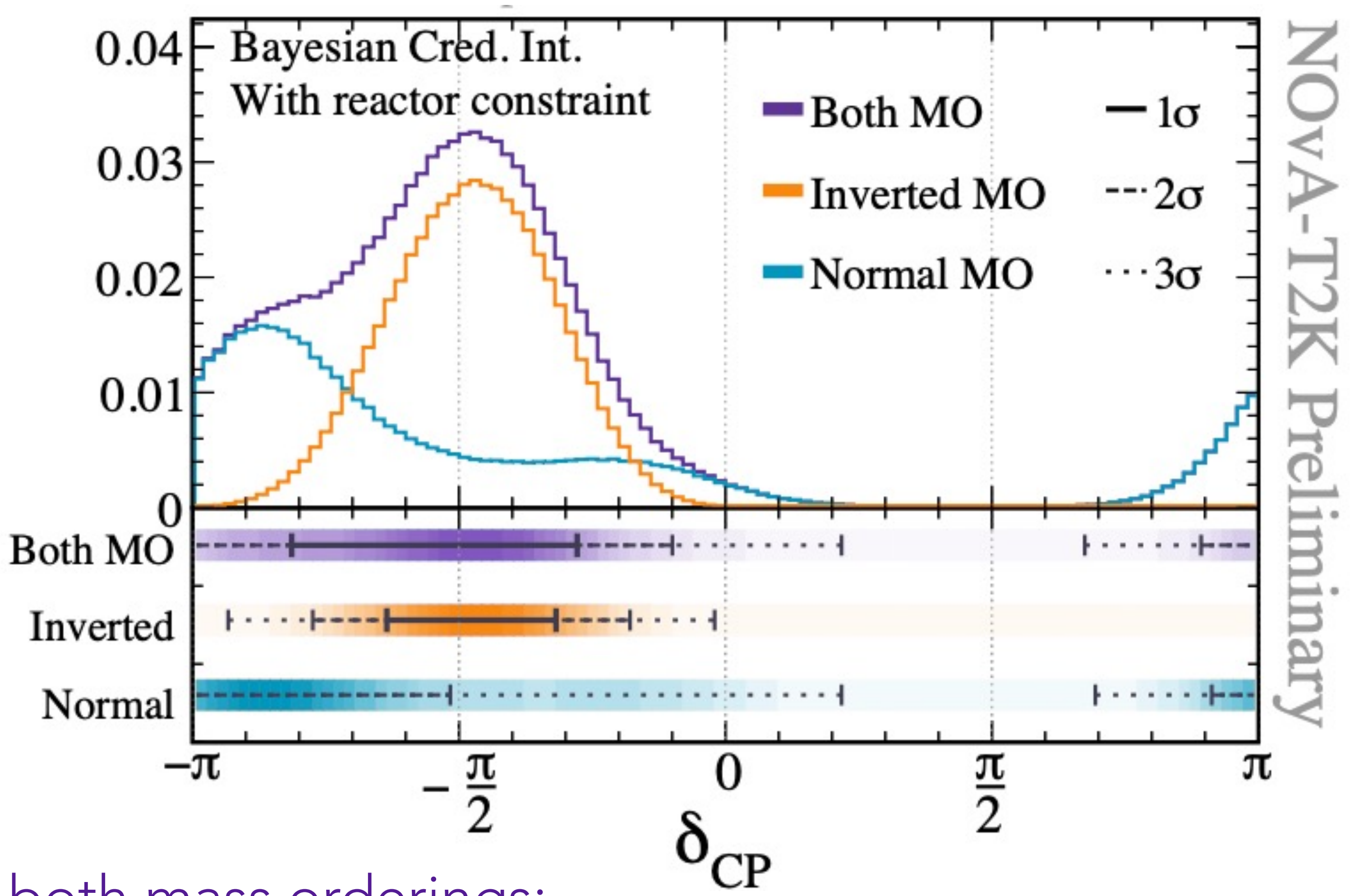
Mixing Angles: θ_{23}

	NOvA - T2K w/o reactor	NOvA – T2K – w/ reactor
Bayes factor	1.17 (~54% C.I) (Lower Octant/Upper Octant)	3.58 (~78% CI) (Upper Octant/Lower Octant)





CP Violation

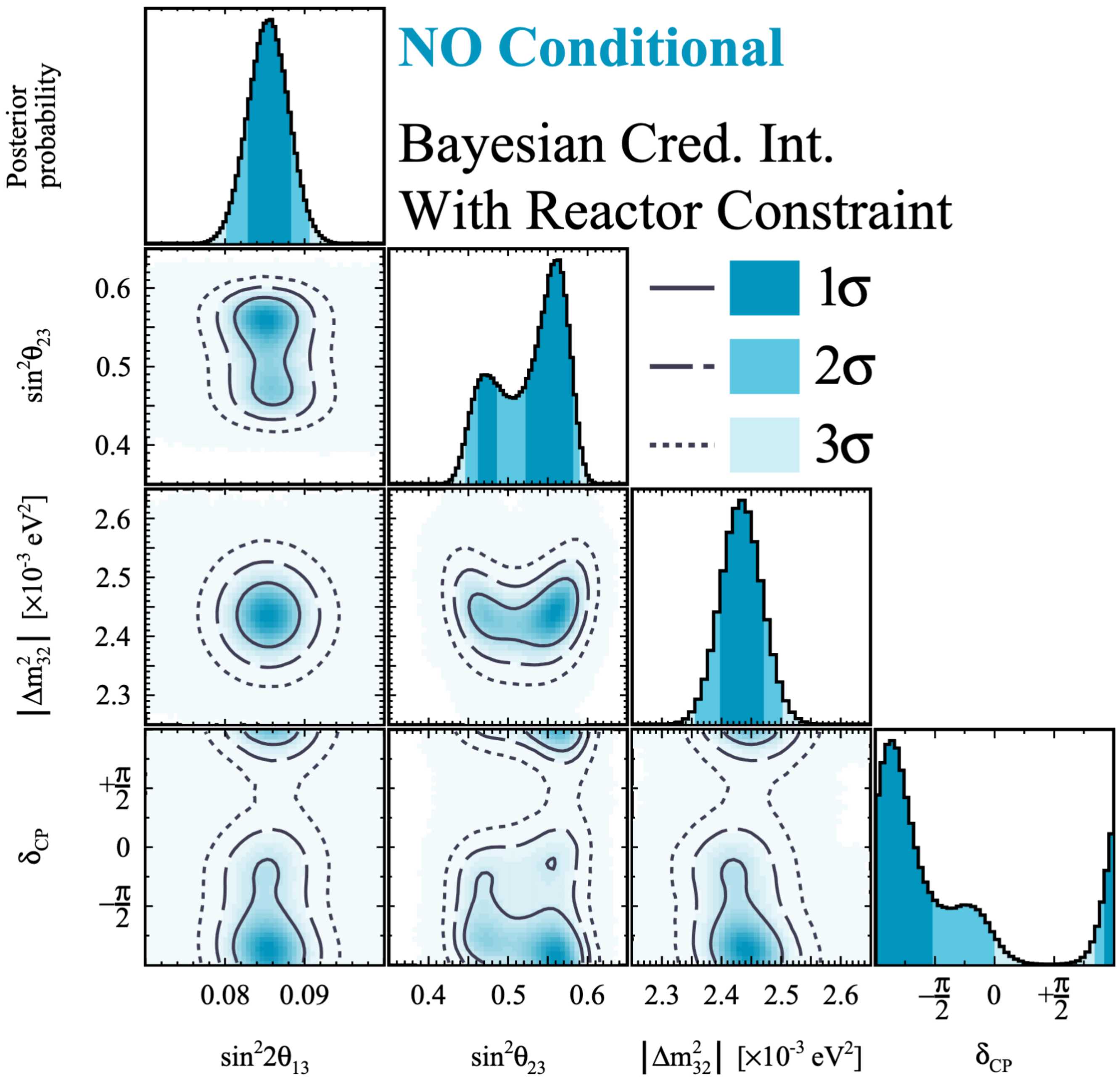


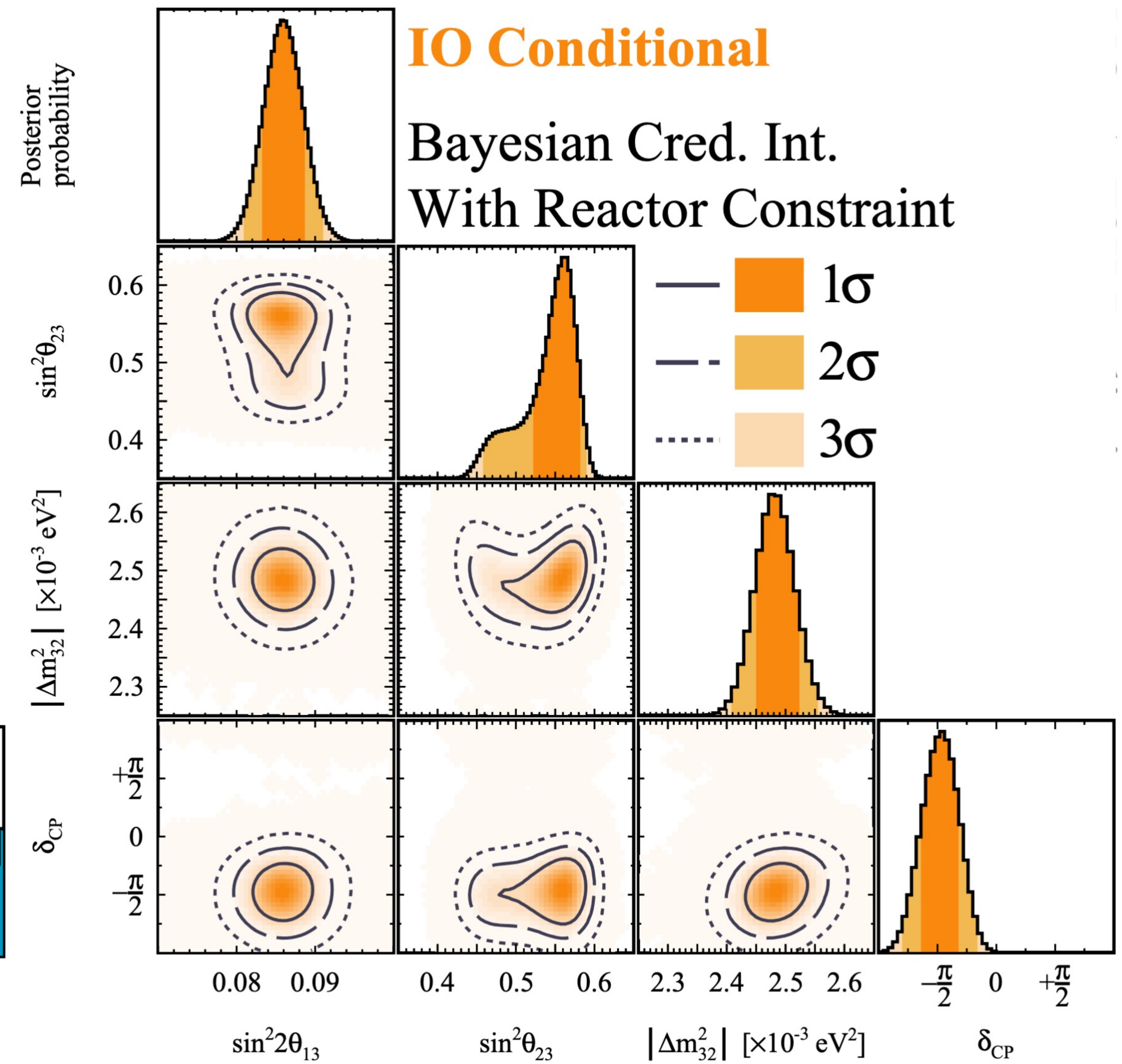
- For both mass orderings:
  - $\delta_{CP} = \frac{\pi}{2}$ lies outside of the 3σ credible interval.

- In the Normal Ordering:
  - Broad range of permissible δ_{CP} values.

- In the Inverted Ordering:
  - CP conserving values $\delta_{CP} = 0$ and $\delta_{CP} = \pi$ lie outside the 3σ credible interval.

An Overview


NO Conditional
Bayesian Cred. Int.
With Reactor Constraint
1σ
2σ
3σ
Posterior probability
$\sin^2\theta_{23}$
$|\Delta m^2_{32}|$ [×10⁻³ eV²]
δ_{CP}
$\sin^2 2\theta_{13}$


IO Conditional
Bayesian Cred. Int.
With Reactor Constraint
1σ
2σ
3σ
Posterior probability
$\sin^2\theta_{23}$
$|\Delta m^2_{32}|$ [×10⁻³ eV²]
δ_{CP}
$\sin^2 2\theta_{13}$